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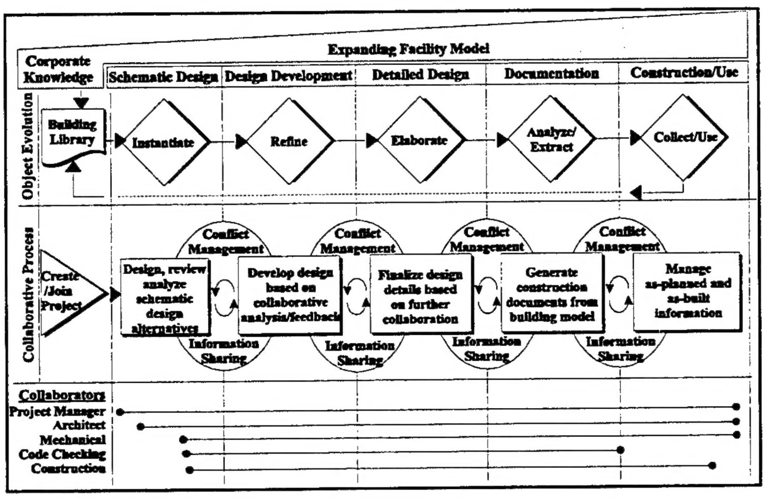
January 1998

Applying Collaborative Engineering to the Facility Delivery Process

A Testbed Demonstration

by Beth A. Brucker and Annette L. Stumpf



Researchers at the U.S. Army Corps of Engineers Construction Engineering Research Laboratories (USACERL) have been developing a collaborative engineering (CE) software environment to enable sharing of design information as it is created and refined during the facility design and construction process. Improved information sharing capabilities and conflict management during collaborative design enables a team to resolve design issues and conflicts earlier in design development, resulting in an improved facility design, fewer errors and omissions, and better interdisciplinary coordination of design goals and building systems.

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An important part of the CE research program at USACERL is the development of an integrated information model that allows agents to communicate/collaborate over the life cycle of the project. This report presents a CE environment that was developed to support collaboration among design and construction agents. Lessons learned during this case study will be used to reengineer the facility delivery process using a CE approach.

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Foreword

This study was conducted for the U.S. Army Corps of Engineers (USACE) under Project 4A162784AT41, "Military Facilities Engineering Technology"; Work Unit AR7, "Domain Knowledge Structure and Process." The technical monitor was Daniel Duncan, CEMP-EA.

The work was performed by the Engineering Processes Division (PL-E) of the Planning and Management Laboratory (PL), U.S. Army Construction Engineering Research Laboratories (USACERL). The authors gratefully acknowledge the contribution of members of the Engineering Processes Division at USACERL who are involved in the ongoing research effort, Kirk McGraw, Eric Griffith, Jeff Heckel, Rasharam Ganeshan, Phil Lawrence, Susan Presser, and Mike Fu. Dr. Michael P. Case is Chief, CECER-PL-E, and L. Michael Golish is Operations Chief, CECER-PL. The USACERL technical editor was Linda L. Wheatley, Technical Information Team.

COL James A. Walter is Commander of USACERL, and Dr. Michael J. O'Connor is Director.

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Background

The life-cycle cost, quality, durability, and reusability of facilities built for the U.S. Army and other military services is important during an era of increased competition for declining resources. More money is spent on the salaries and benefits of the people working or living in a facility than is spent on designing, building, maintaining, conditioning, and operating the facility during its useful life. According to Thomas R. Rutherford, P.E., Assistant for Engineering and Construction, Office of the Secretary of Defense, "People costs consume more than 95 percent of all costs in terms of building life-cycle cost evaluations, when the cost of the people in the building are included" (Rutherford 1997). Often, military facilities are used, reused, remodeled, and renovated for many years past the original anticipated life. Also, military facilities often have unique requirements, special restrictions, or hostile environments which can complicate the design/construction process.

The Department of Defense (DOD) spends $8.8 billion annually on new construction, $94 billion on operation and maintenance (O&M) of facilities, and has a $14 billion backlog of maintenance. On 8 July 1997, the U.S. House of Representatives approved $9.2 billion in new spending authority for military construction. While the measure is nearly $800 million above President Clinton's Fiscal Year (FY) 1998 budget request, it is $610.3 million less than in FY97, reflecting a 6-percent reduction. According to LTG Joe N. Ballard, Commander, U.S. Army Corps of Engineers (USACE), military budgets will not even keep up with the cost of inflation in the foreseeable future. Therefore, a way must be found to use scarce resources more effectively, and to reengineer business practices to improve productivity while permanent civilian staff positions are being cut (USACERL Townhall Meeting, 27 June 1997).

The Army Corps of Engineers manages the design and construction of military facilities, civil works projects, and environmental remediation projects for the Army and other customers. Private A/E firms designed approximately 75 percent of the facilities built for the Army in FY95 at a cost of $319 million.

Almost all of the $4.2 billion in Army construction in the United States was accomplished by private sector firms during FY95. Substantial savings could be realized by placing more emphasis on optimizing the facility design to reduce costs over the facility's life cycle.

Each project typically involves many people: owner representatives (from the using agency and host installation), contracting officers, designers and consultants (in-house or contracted), reviewers (design, constructibility, operation, functionality, and maintenance), and builders (typically private sector contractors). A typical Military Construction - Army (MCA) project can last 3 to 5 years from initial project scoping to completion of construction and is governed by procurement, design, energy, construction, and other regulations. This facility delivery process includes periodic design reviews, yet may not ensure that the completed facility satisfies client requirements, which can change during the 3- to 5-yr process. A large project such as a medium-sized hospital might take even more time—up to 8 years—to plan, design, construct, and commission. Another complication is that the military often constructs facility types unfamiliar to the commercial Architectural/Engineering (A/E) firms and contractors who design and build them.

Several business reengineering studies and working groups have concluded that the facility delivery process should be improved by reengineering the process, shortening delivery time, and using computer technologies to improve design/ engineering productivity.

At the 1996 Worldwide Area and Resident Engineer and Contracting Training Seminar, MG Albert J. Genetti, Jr., Director of Military Programs, discussed the Corps Vision: "Being a vital part of America's Army, building for the future and providing quality, responsive engineering services to support the Nation in Peace and War..." and his goal for the Corps to become a "Seamless Team" to our various customers. He spoke briefly about ongoing Army-wide efforts to reexamine and reengineer its construction function. The Corps led an Army-wide effort of major Army command (MACOM) representatives to recommend to Army leadership how the Army could better support the construction, engineering, environmental, and real estate needs of its installations. Key study recommendations are to look at more privatization or outsourcing of functions, streamline management processes, and find smarter ways to do business. MG Genetti specifically mentioned MDS (Modular Design System) as a bright possibility for the future [U.S. Army Corps of Engineers, June 1996]. He also said, "Quality is as important as execution. Quality is our most important product." Key capabilities of the testbed technology described in this report are being incorporated by USACERL into future versions of MDS.

The Army Corps of Engineers is developing campaign plans to implement the Corps' Strategic Vision authored by LTG Ballard (USACE 1997). The 1997 HQUSACE Campaign Plan shows that Team 4 (Virtual Team Initiative) is co-chaired by the Directors of Information Management and Human Resources. Their task is to:

> develop and implement, by 15 September 1997, a plan to promote "virtual teams" in the Corps of Engineers. The plan will include identifying the technical means, cultural gaps, changes to policy, training needed, executive responsibilities, and management systems necessary to create the environment needed for virtual teams. The plan must allow the Corps to be rapidly responsive and flexible—an organization able to adapt, tap talent and expertise, distribute work, and produce engineering products and services without the need for either physical reorganization or co-location of resources. The plan will leverage advanced information technologies and the right kind of organizational climate—one with supportive culture and relationships. Corps members will have seamless access to information and ease in performing data aggregation, summarization, and retrieval. The goal is to improve communications, customer satisfaction, and services and to facilitate the "one door to the Corps" concept. This may require challenging basic assumptions about the organization and norms.

Collaborative engineering (CE) software that would allow teams of people in various locations to design facilities is essential for virtual design teams.

Engineering Focuses and Initiatives listed the following focuses: (1) simplification of design process, (2) quality design, (3) cost of doing business, (4) partnering, (5) installation support, and (6) combat readiness support. During recent years, the number of Army-unique/Federal/military specifications have been dramatically reduced, being replaced with mostly commercial or industry-wide standards (HQUSACE, December 1995). On 16 February 1995, LTG Arthur E. Williams, then Chief of Engineers, issued a Master Action Plan (MAP) requiring all USACE solicitations issued after 10 October 1995 to be either free of military specifications (MIL-SPECs) and military standards (MIL-STDs) or have waivers in place for those remaining. Another pending design process change, which will begin with the FY98 military construction (MILCON) program, is the replacement of the "35% design phase" with a "Project Engineering (PE) phase" using parametric estimating and a design charette process. The only exceptions to this change will be those projects of a complex or unique nature for which there is little or no historical design and cost data (USACE, 4 April 1997). Other initiatives being studied are ways to improve engineering and design productivity through the use of computers and digital technologies, simplified design, a streamlined review process, timely coordination and teamwork, and restructuring and reengineering the Corps organization.

A recently released Civil Engineering Research Foundation (CERF) report (CERF 1996) lists 38 research topics or challenges facing the construction and engineering industry with respect to environmentally sustainable infrastructure. Generated by a global team of more than 700 construction and engineering experts, the Global Research Agenda calls for innovation in technology based on seven themes:

- applying global standards and performance criteria
- utilizing demonstration projects to accelerate innovation
- expanding the industry base
- streamlining the construction process
- creating new tools and methods
- bringing understanding to industry, government, and the public
- defining sustainability operationally.

Participants were divided into five industry groups:

- Management and Business Practices
- Design Technologies and Practices
- Construction and Equipment
- Materials and Systems
- Public and Government Policy.

The Management and Business Practices group placed heavy emphasis on Streamlining the Construction Process. USACERL's CE research effort is specifically mentioned in Focus Area 1: Management and Business Practices, Topic 1.9, Promoting Seamless Knowledge Transfer in Construction. The objective of this topic is: "To promote, coordinate, and monitor existing and new efforts that establish common global protocols for storage and transfer of information regarding all aspects of the design, construction, and operation of built facilities."

The Creating New Analytical Tools and Methods group research topics are also related to USACERL's CE effort. The overview emphasizes that collaboration is the key to the engineering and construction industry's success in the next century. This technology gap can be bridged by developing a truly collaborative design environment.

Even with existing Computer-Aided Design (CAD) automation, many opportunities exist in the current design process to improve the quality while reducing errors and total life-cycle costs. Drawings and other information developed during the design phase are not readily incorporated into information systems

required for construction management (i.e., project management, scheduling, progress payments) and O&M (i.e., Engineering Management Systems [EMS], Computer Aided Facility Management Systems [CAFMS]). This situation applies to both government-supported and commercial off-the-shelf (COTS) software. Additional benefits would be gained by reducing errors in construction documents and improving tradeoffs between competing engineering goals in facility design. Better as-built documentation is desired by those who manage and maintain the facilities.

Use of a CE design environment that enables all design participants to add and share information throughout the design and construction process would greatly improve communication and coordination. A structured information infrastructure could support computable facility models throughout their life cycle as they are developed during the design phase and passed downstream to construction management and O&M phases. An integrated information model not only encourages those involved in construction to use and add to design information, but also provides richer information representation, better efficiency and data consistency, and the flexibility to support life-cycle information management. The resulting facility model, in combination with as-built documents in a structured electronic format, could serve as the foundation for all information about the facility during its life cycle.

It is, therefore, essential that the multidisciplinary teams who design, build, and operate such facilities have access to collaborative design tools and an integrated information model that allows them to share current information, avoid redundant input, access appropriate analysis tools, detect conflicts, and collaborate with other team members both in the same office and at other locations.

Objectives

The objective of this research was to develop an integrated information model to allow collaboration over a project's life cycle. CE is a technology-based design and construction management approach that emphasizes four principles: (1) simplification of existing serial design and construction processes, (2) global optimizing of facility design through support for team collaboration, negotiation, and group decisionmaking, (3) incorporation of downstream requirements such as maintenance, operations, environment, and other life-cycle issues into the design process, and (4) development of robust, integrated product and process model representations that can evolve and be used throughout the facility life cycle.

A fully implemented collaborative environment will significantly improve the quality of decisionmaking, contract documentation and related design processes. Through agent-assisted collaboration, the extended design groups (including construction, operations and maintenance [O&M], and other installation personnel) work as a coordinated team. Software agents will assist designers in making decisions based on improved information dissemination and conflict management. Designers will have the capability to effectively consider a wider variety of design solutions and evaluate additional alternatives to improve the quality, health and comfort, energy efficiency, and life-cycle cost effectiveness of the facility. Making these types of analyses easy to perform will mean facilities that perform better functionally and at reduced operational expense.

Scope

This report describes a hardware and software environment that illustrates the following key CE goals:

- a shared workspace that allows participants to view common elements of a facility design, while at the same time providing legitimate privacy needs
- a common communication protocol and representation schema for design information
- identification of conflicts between design participants
- a capability for participants to use software-based agents to represent them in the design process
- an open architecture that allows participants to link industry standard CAD, database, analysis software and custom applications into the CE software environment.

The research presented in this paper was performed under the auspices of the CE research program at USACERL, which is attempting to redefine existing design processes to make them more collaborative and develop enabling technologies to support the new process. An important part of this research is the development of an integrated information model that allows agents to communicate/collaborate over the life cycle of the project. This report presents a CE environment which was developed at USACERL to support collaboration among design and construction agents.

USACERL's case study or design *testbed* demonstrates how design information evolves during the design development and construction planning phases of a facility. Lessons learned during this case study will be used to reengineer the facility delivery process using a CE approach.

Approach

The testbed project was a coordinated effort to produce a demonstration of integrated software tools and agents which can perform collaborative design and analysis tasks using a shared facility model. Key aspects of the testbed which were studied for this report include:

- technology
- scenario
- agents
- shared facility model
- collaborative design process.

The CE research program at USACERL has been an ongoing effort for the last 3 years and is composed of several research projects. The following USACERL projects participated in the testbed demonstration:

Project Title	Work Unit #	Principal Investigator
Closely-coupled Collaborative Workspaces	AT23-FF-EA5	Phil Lawrence
Generative Design Strategies	AT23-FF-EC5	Eric Griffith
Agent Collaboration Language	AT23-FF-EF5	Michael Case
Construction CADD	AT41-FF-AS5	Annette Stumpf
Generative Design Methods	AT41-FF-AG5	Eric Griffith
Domain Knowledge Structure and Process	AT41-FF-AR5	Beth Brucker
Design Reviewer's Support Environment	AT41-FF-AP5	William East
Agent Based Collaborative Methods for Energy System Design	AT45-FE-X55	Kirk McGraw
Expert System Analysis & Concurrent Engineering for ESD	AT45-FE-XS5	Michael Case

As a part of this effort and related USACERL projects, the following tasks were accomplished:

- the current MCA design/construction process (facility delivery process) was analyzed
- efforts to improve the MCA process were identified, along with case studies and targeted areas for improvement
- current design tools, CAD standards, and A/E deliverables were investigated
- a subset of the MCA design activities was chosen for this project
- the testbed scenario and new collaborative design process were developed
- identified which "agents" should be developed to implement the scenario

- developed shared object-oriented (O-O) facility model
- conducted two literature searches of available technologies and tools (Case et al. 1994, Ganeshan 1996)
- selected most suitable CE software technologies, assuming legacy tool integration
- developed/integrated:
  - software tools with the collaborative design environment using the Agent Collaboration Environment (ACE)
  - conflict resolution
  - CAD talk
  - commercial software tools such as BLAST*, Microsoft Project, Microsoft Excel, MCACES, AutoCAD, and MicroStation
- developed agents (Project Management, Architectural Layout, Construction Planning, Cost Estimating, Roofing Design, Code Checking)
- tested all the research products listed above using a fire station and battalion headquarters as a case study project
- documented the testbed research and lessons learned in several USACERL technical reports, presentations, and conference papers.

While the testbed research was proceeding, USACERL also directed and participated in a related collaboration effort, called Agent Collaboration Language (ACL) in cooperation with several universities, including the University of Illinois at Urbana-Champaign (UIUC), Stanford University, Carnegie Mellon University (CMU), and the Massachusetts Institute of Technology (MIT). This parallel effort attempted to enable collaborative design and analysis by translating between participants using different facility models. The ACL project used Stanford University's Facilitator Architecture to translate between different domain schemes. UIUC conducted energy analysis for the facility using BLAST, CMU used SEED† for architecture layout, MIT performed structural analysis, and USACERL managed the project (Khedro et al. 1995 and 1996).

Mode of Technology Transfer

USACERL has signed a Cooperative Research and Development Agreement (CRaDA) agreement with GoldHill, Inc., to develop a commercial product based on ACE.

* BLAST = Building Loads Analysis and Systems Thermodynamics.

† SEED = Software Environment To Support Early Phases in Building Design.

Many of the concepts and software tools developed during the testbed project will be incorporated in future versions of design software called the Modular Design System (MDS). The MDS CRaDA was signed 18 July 1996 with Bentley Systems, Inc., Building Systems Design, Inc., IdeaGraphix, Inc., and JMGR, Inc. USACERL is responsible for execution of research and development (R&D) in support of MDS. In addition to Army Corps of Engineers organizations (HQUSACE, USACERL, WES, and the Louisville Engineer District), the MDS Development Team includes the U.S. Army Reserve, the Army National Guard, and the industry partners listed above. The University of Southern California, UIUC, and CMU are also involved in this collaborative effort (Case 1997).

Four members of the testbed project are actively contributing their experience and expertise in developing a shared facility model with the International Alliance for Interoperability (IAI). IAI is developing Industry Foundation Classes (IFC) that will enable IFC-compliant software to exchange an object-oriented facility model. The IAI is a nonprofit alliance of the building industry including: architects, engineers, contractors, building owners, facility managers, building project manufacturers, software vendors, information providers, government agencies, research facilities, and universities with member chapters in North America, Germany, the United Kingdom, France, Singapore, Nordic countries, and Japan. Its mission is to integrate the AEC/FM industry by specifying IFC as a universal language to improve the communication, productivity, delivery time, cost, and quality throughout the design, construction, and O&M life cycle of buildings. The Alliance is committed to taking advantage of the collective power of the industry to produce a standard for communication promoting collaborative efforts and global expansion. The IAI IFCs will serve as an information infrastructure for future versions of MDS software (IAI 1997).

Incorporating concepts and technology developed during the testbed project, "Project CITY" is a joint program of the Army and the National Science Foundation High Performance Computing and Communications program (Lu et al. 1994). The project is developing a workbench of software tools, CITYSCAPE, that will help improve teamwork in public works management.

Ultimately, if IAI IFCs become industry standard, and the Tri-Services CADD Center endorses them as a portion of future CAD standards, Corps of Engineers Districts and Divisions; Headquarters, U.S. Army Corps of Engineers, other DOD and government agencies engaged in the acquisition of facilities, and the construction industry at large will be able to produce computable designs that can be developed and exchanged using commercial design and analysis tools.

MDS Version 2.0 was delivered 15 April 1997. Scheduled for delivery in October 1999, MDS Version 3.0 will be based on an open, object-oriented technology developed through partnering with leading vendors and A/E firms. MDS Version 4.0, planned to be available in October 2001, will add CE capability to allow virtual teams to work together over the Internet.

2 Opportunities for Improvement in the Design/Construction Process Using Collaborative Engineering Tools

Introduction

The Army is the largest facility owner in the Federal Government. Its facility delivery processes must be improved in order to meet existing and future requirements, despite reduced personnel and funding. In the context of this report, facilities refers to buildings (e.g., armories, Reserve centers, barracks, training centers) that are designed, engineered, and constructed by the Army Corps of Engineers, Army Reserve, National Guard, and Air Force. Although conventional facility-delivery processes and practices successfully produce facilities, these facilities frequently are not delivered in time to meet the original requirements and can exceed the established budget. By the time a facility is delivered, user requirements can be nearly 5 years old, the delivered facility may only satisfy a portion of updated requirements, and the cost is excessive. As discussed in Chapter 1, drawings and other information developed during the design phase are not readily incorporated into information systems required for construction management and O&M. This incompatibility applies to both government-supported and commercial software.

Computer-based Project Information Management System

Enabled by low-cost yet powerful personal computers (PCs), the Architectural/Engineering/Construction (A/E/C) industry is using computers intensively in their tasks. Similarly, facility operators and maintainers are given plenty of choices of facility management software to plan and execute the day-to-day operations. Computer-based systems have increased the quality, productivity, and efficiency of design, construction, and facility O&M. Accompanied by these improvements come the challenge and opportunity to transfer integrated information from one entity to another, and from one phase to another. What is desired is an integrated information management structure that supports activities throughout the life of a facility—an integrated system for consistently

managing drawings and project information during facility design, construction, and O&M. Ideally, a system that is used by designers and engineers can be updated by contractors to post changes and as-builts, and eventually can be used by facility operators and maintainers to manage their tasks. Figure 1 shows the concept of ideal facility life-cycle information integration from design to disposal of a facility. The bins represent information created, shared, refined, and added to the facility model during each stage of the facility delivery process. The figure shows an electronic model of the facility created during design, using either intelligent CAD drawings or object-oriented 3-D CAD drawings with data associated to the drawing elements (or objects). At each subsequent stage of the facility delivery process, relevant information is added to the facility model, including as-built information, warranties, and O&M information. The resulting facility model can then be used throughout the facility's life cycle. This information integration not only provides the needed information infrastructure to store/retrieve life-cycle information, but also reduces inconsistent and inaccurate information. Because of the large amount of data, all information is stored on CD-ROMs (Stumpf et al. 1995).

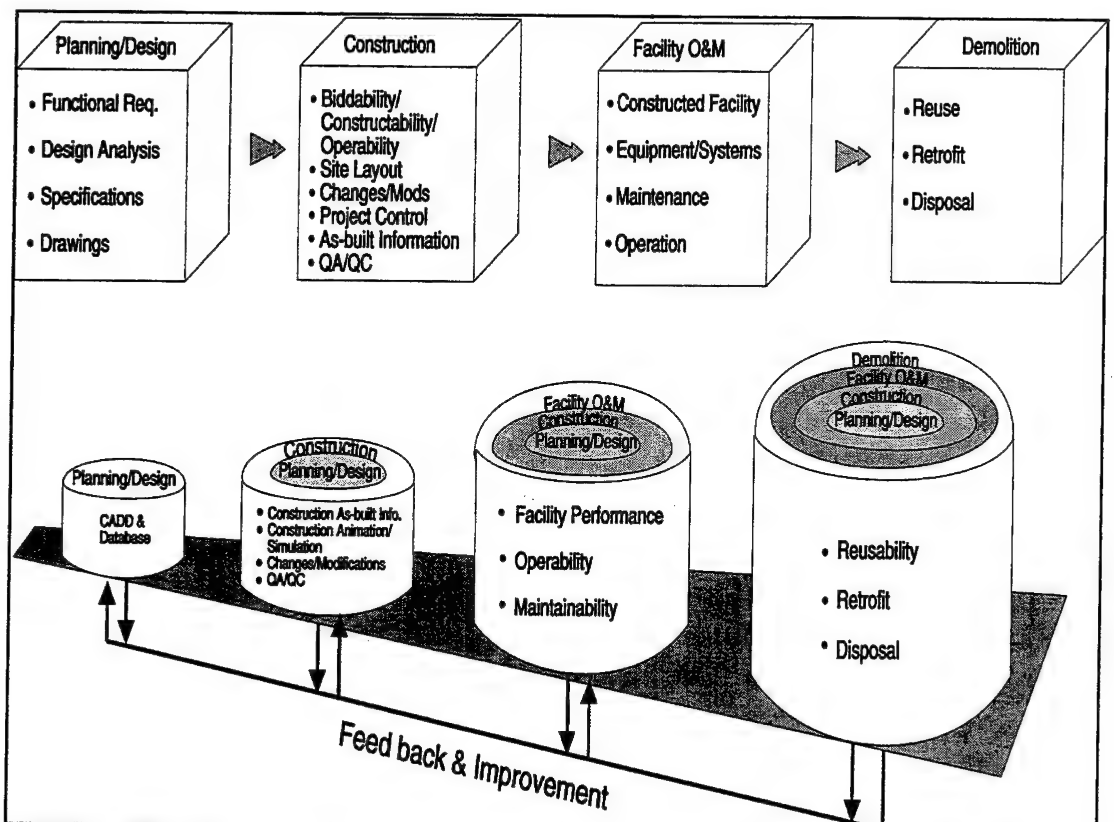

Figure 1. Facility life-cycle information management.

Total Quality in the Facility Design Process

Total quality is a client-focused, strategic, and systematic approach to the continuous improvement of performance. Total Quality Management (TQM) is a management method to improve the quality of the work we do. When analyzing the facility design process, this means that efforts must be made to measure and evaluate the existing process, identify the sources of problems, and optimize or reengineer the process (sometimes radically) to reduce unnecessary activities, eliminate errors, and speed the process.

Without metrics, it is impossible to determine if a change to a process is beneficial or if it improved quality. Quality can often be measured either by qualitative or quantitative measures. Most tools used in TQM were developed for quantitative analysis primarily aimed at the manufacturing of products, not services. Emphasis is placed on counting errors as a percentage of total products manufactured. Statistical analysis requires measurable, objective data, which is best obtained in producing tangible products.

The construction industry is fundamentally different from manufacturing in quantity of products being designed. The manufacturing process provides significant feedback because of the sheer numbers of goods being manufactured from a single design. Quality control provides feedback allowing the design to be improved over time. On the other hand, the construction industry rarely builds more than one facility from a single design. This lack of feedback causes the facility design to suffer and its processes to be less optimized.

Measures of Quality

Quantitative measures do exist in architecture. Various metrics such as the net-to-gross ratio, unit and system cost metrics, cost growth through change orders, or hours to complete a drawing sheet are all useful measures. However, few relate directly to quality as it would be understood by most architects.

As a result of TQM, there is now interest in finding metrics related to the design process itself. One study identified both short- and long-term metrics that could be used for the design process (Culp, Smith, and Abbott 1993).

Short-term metrics.

- number of scheduled milestones missed
- amount of overtime by staff
- cost of drawing/specification rework after final check

- number of inconsistencies between drawings and specifications
- number of errors per drawing
- hours and/or cost per drawing
- ratio of project engineering/architecture cost to budget amount
- submittal (shop drawings) review time
- response time to contractor requests for information
- number of typographical errors per page on resume, report, or other printed work.

Long-term metrics.

- turnover rate of technical staff
- success rate on proposals submitted
- project budget overruns (frequency and amount)
- cost of marketing as a percentage of total fees
- number of times a document is changed after it is issued
- number of formal reviews conducted on time
- dollar amount of field changes
- number of contractor requests for information
- change orders, expressed as percentage of project construction costs
- ratio of final construction cost to estimated construction cost
- client perception of project quality and consultant responsiveness
- claims, settlement, and litigation expense.

The University of Maryland's Architecture and Engineering Performance Information Center (AEPIC) used litigation as a metric directly related to the quality of the facility and/or its process. AEPIC analyzed 5,000 buildings and 2,500 civil works projects that suffered from performance failures. The data analyzed were primarily from professional liability cases, the ultimate measure of quality. Performance failures in this report are defined as "the results of the unfulfillment of a claim, promise, request, need, or expectation between the design professional, contractor, owner, user, or any other party to the building process."

AEPIC found that five building systems (mechanical, roofing, structural, sitework, and envelope) were responsible for 52 percent of the total incidents. For these claims, 41 percent were the result of architectural services, 34 percent were engineering services, and 16 percent were for construction services. When looking at the reasons for performance incidents, 44 percent were for design services, 17 percent were for construction services, and 7 percent were for specification writing (Loss 1991).

Emphasizing the TQM process, the Corps of Engineer's Louisville District created a Cost of Doing Business Process Action Team (CODB PAT) to study how architects and engineers do business in their organization. Using metrics similar to those discussed above, the PAT set out to examine new strategies to save design time, save money, and to standardize design procedures. They wanted to develop a new design process to make their A/E Division more efficient and cost effective, enhancing the Corps' image and making them more competitive. One of their major conclusions was the need to have a greater emphasis on the "team concept." They felt the team concept offered a forum for promoting a strong partnering agreement with the customer. It would also allow designers to talk face to face with individuals who will be reviewing the project to find out their expectations while still being able to gather the necessary information to start project design (Basham et al. 1993).

The team concept and identification of other metrics that directly relate to the design are useful in looking at the process and, in particular, the breakpoints and time-consuming efforts within the process. With this in mind, USACERL studied the traditional process in the Corps of Engineers as it relates to the team concept, which is now enhanced with the development of CE systems, the Internet, and the World Wide Web.

The Army Facility Delivery Process

USACERL researchers have been working to improve both the facility delivery process and the quality of the constructed facility. Leverenz et al. (1983) analyzed the MCA building delivery process to identify the process steps, phases, participants, decision points, legal and technical requirements, and products. All regulations pertaining to the MCA process and energy-related issues were analyzed to determine the energy impacts of design and construction decisions. Similar investigations were conducted on two variations of the traditional two-step building delivery process: (1) the Army Design/Build process (Napier 1990) and (2) the Army Third Party Construction process (Napier 1993). Then USACERL developed a detailed "Discourse Model" of how participants collaborate during the design process (Case 1994 and 1996). Building upon this research, the entire facility delivery process was analyzed and documented in detail (Stumpf et al. 1996). The traditional design process was studied, along with recent efforts to improve the process. Next, the construction process was analyzed from the Resident Engineer's viewpoint to determine: (1) the type and format of design information that goes into the construction process, (2) how Resident Engineers use the information during construction, (3) what kind of as-

built and project control information is collected during construction, and (4) the type and format of the as-built information delivered to the facility's owner. Special attention was given to the use of CAD technologies and information systems used by Resident Engineers during the construction phase (Stumpf 1994). A study of as-built project information used (and desired) during facility management and O&M was also conducted (Liu 1994). Finally, a new design process was developed to enable designers to effectively use the new CE and communication technologies to improve the facility design while shortening the facility delivery process.

Traditional MCA Facility Delivery Process

Participants, responsibilities, and products/documents. The facility design and construction process involves many participants, from various organizations, who create, change, analyze, evaluate, and comment on a large volume of shared and proprietary design alternatives and information until the design is finalized. Even after construction begins, further changes and modifications are needed. Before the facility can be handed over to the owner, accurate as-built and project control information must be collected to describe the actual components which were purchased and installed in the facility (Stumpf 1996).

Figure 2 depicts the participants and major activities that occur during the MCA design and construction process. Table 1 shows responsibilities, requirements, and products at each phase of the process. Funding for each MCA project must be approved by Congress as part of the overall Army Stationing and Installation Plan and the Long Range Construction Plan. A limited construction budget is available, and all projects are prioritized and ranked. Only those at the top of the list are funded each year. This budget approval cycle repeats each year, while budget constraints increase, and new construction priorities appear. Once funding is approved for an MCA project, the design and construction process typically takes between 3 and 5 years, unless the building is large and very complicated, such as a hospital or chemical demilitarization plant.

Traditional Design Process

Figure 3 diagrams the flow of the traditional design process and its activities, and demonstrates when the participants join the process (Brucker 1995).

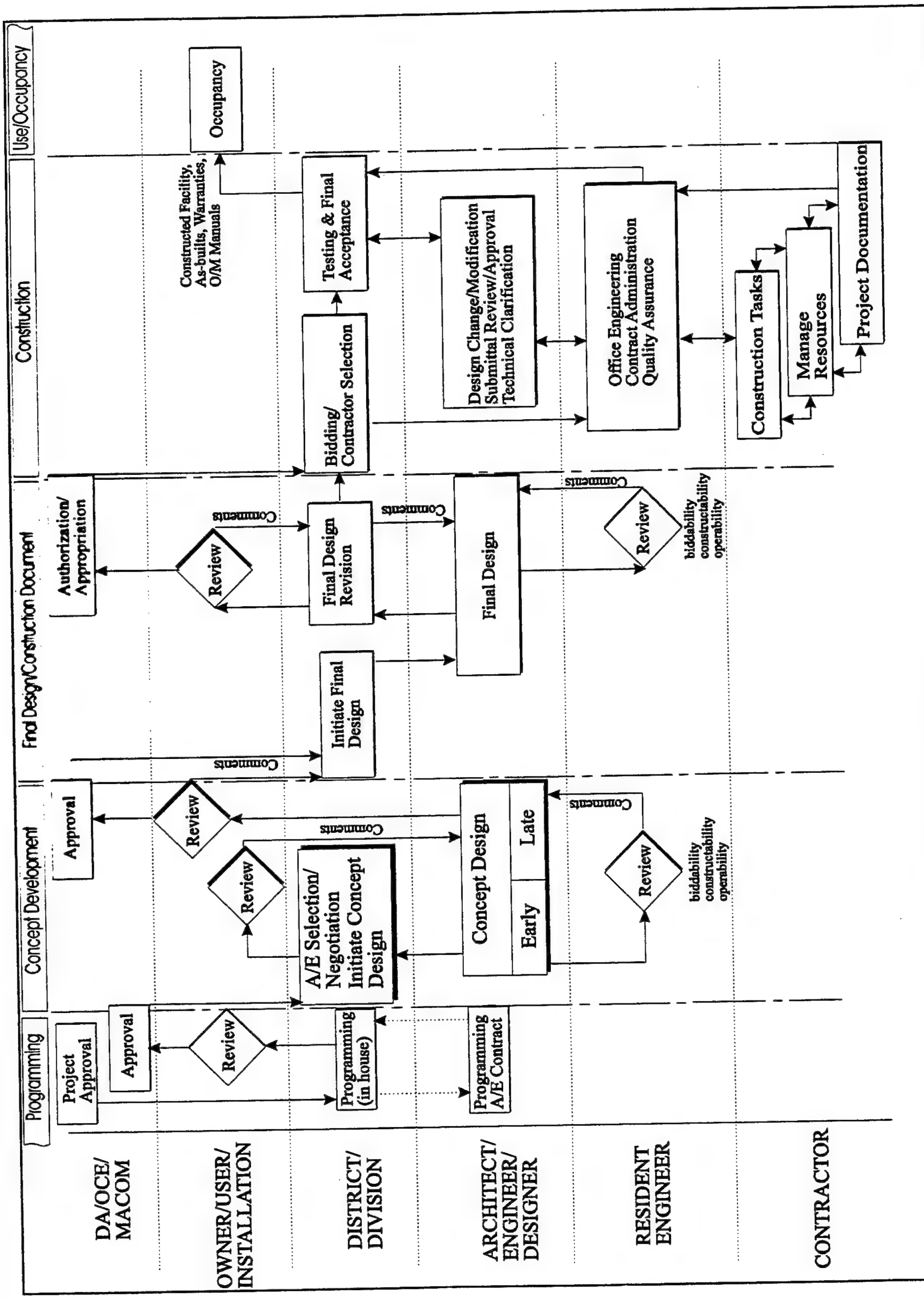

Figure 2. Design/construction process of Military Construction, Army.

Table 1. Participants, responsibilities; and products of Military Construction, Army process.

Participants	Responsibilities	Products / Documents
Department of the Army (DA), Office of Chief Engineer (OCE), MACOM	Functional and Capability Planning Analysis Prioritize Projects Request Funding Authorization from Congress Manage Design and Construction Program Update Design and Construction Requirement	5 Year Defense Program Army Stationing and Installation Plan Long Range Construction Program
Owner/User Installation	Identify Training and Facility Requirements Evaluate and Select Site Assess Environmental Impact Determine Functional and Technical Requirements Design Review and Approval, User Changes Construction Coordination, Acceptance	Installation Master Plan Real Property Requirements Environmental Impact Statement (if required) Detailed Site Plan Architectural Program (Functional/Technical Requirements) FORM 1391, Cost Estimate (Scope and Budget) ARMS (Automated Review Management System)
District or Division	Request Funding Approvals for Programming, Design and Construction Develop Architectural Program (Functional/ Technical Requirements) or Hire A/E Firm Select A/E and Negotiate (Design) Coordinate Design, Review and Approval Bid & Select Contractor (Construction) Expedite Materials, Manage Public Relations Close-out Project (After Construction) Manage Public Relations	Architectural Program (Functional/Technical Requirements) Design Reviews/Construction Changes Design and Construction Contracts Project Management Plan, Upward Reports ARMS (Automated Review Management System)
Design Agency (Corps or A/E Firm)	Prepare Design and Engineering Analysis Prepare Concept and Final Design/Changes Prepare Construction Documents, Specifications Cost Estimate, Value Engineering Review Shop Drawings Analyze Life Cycle Costs	Working Drawings Specifications Design Analysis Detailed Cost Estimate Design Changes During Construction ARMS (Automated Review Management System)
Resident Engineer	Review & Approve Payment Requests Negotiate Change Orders Assure Contractor Quality Review Submittals, Materials, Shop Drawings Assure Customer Satisfaction Review & Analyze Contractor's Progress Prepare Correspondence Monitor Contractor's Safety Program Collect As-Builts, Warranties, O&M Manuals Identify Trends/Lessons Learned Site Coordination Prepare A/E & Contractor Evaluations Review Biddability Constructibility Operability	Contract Plans and Specifications with Modifications, Construction Progress Reports, Site Layout, Schedule Approval, Payment Estimates, QA/QC Plan, Critical Materials/Status, Actual/Anticipated Delays, Record Drawings, Safety Records, Claims, Funding Status, QA/QC Reports, Significant Deficiency Action Plan, Submittal Registers, Shop Drawings, Accident Prevention Plan, Environmental Control Plan, Certified Payroll Register, Affirmative Action Plan, A/E & Contractor Performance Evaluation, Project Meeting Minutes (Prebid, Preconstruction, Construction Quality Control/ Assurance), ARMS (Automated Review Management System)
General Contractor	Perform Contract According to Plans & Specifications, Manage Site, Labor, Equipment, Materials, Time, and Subcontractors. Document Construction Progress, Changes, Quality, Safety, and Others.	Preliminary Schedule, Cost Estimate, Site Layout Progress Reports, Payment Request, QA/QC Reports, Schedule Update, Request for Information, Major Resource Schedule, Samples/Certification/Test Results, Warranties/Operational Manuals, As-built Drawing Update (contract-specific), Shop Drawings, Safety Plan and Records, Daily Manpower and Minority

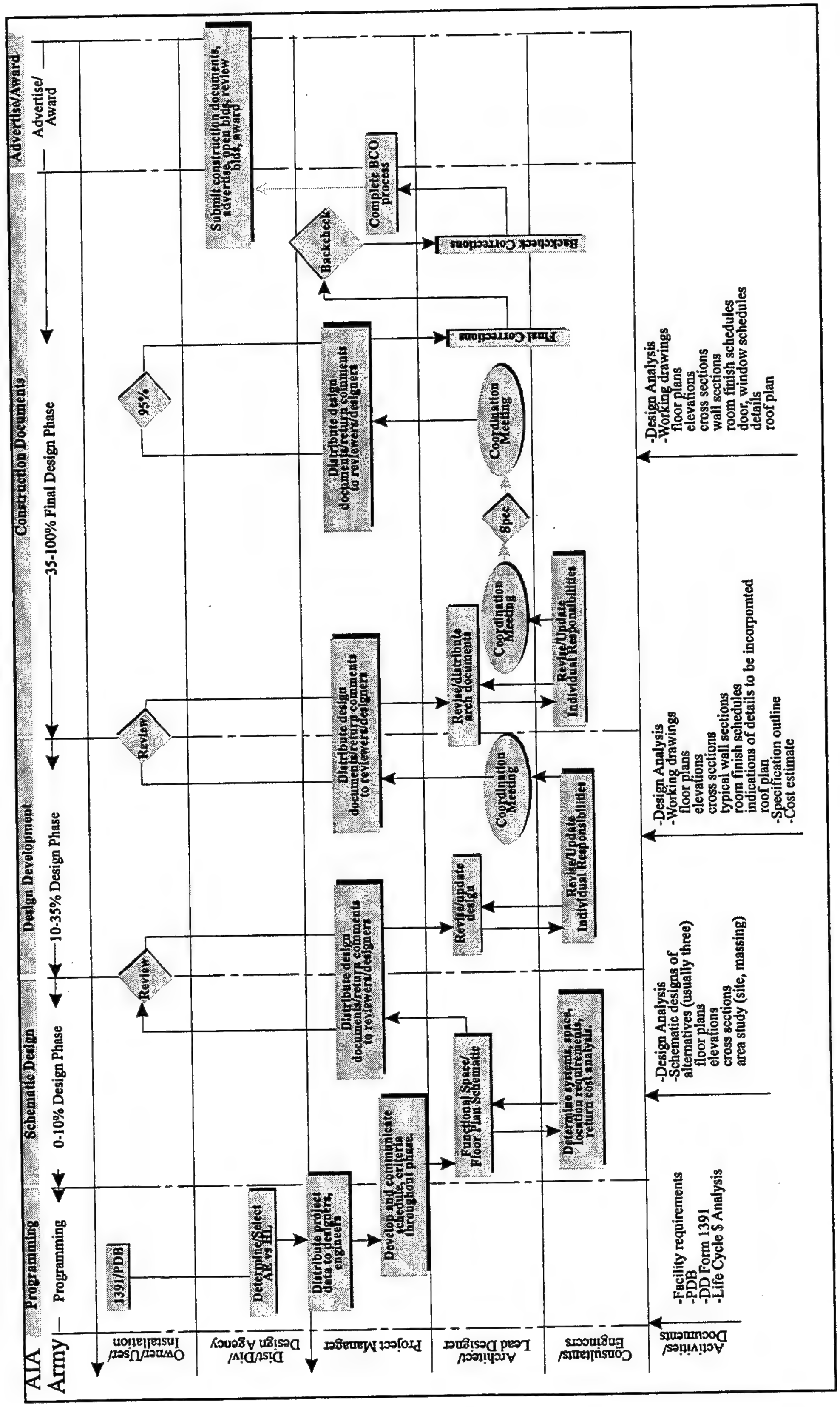

Figure 3. Traditional design process.

The Corps of Engineers follows a traditional Design-Bid-Build approach for most facilities. This process is defined in a Corps of Engineers regulation (Technical Manual 5-800-2) and follows a common approach to facility design for commercial construction. It is very similar to the process defined in the *AIA Architect's Handbook of Professional Practice* (AIA 1987). The AIA document breaks the design phases of the process into three distinct parts: Schematic Design (0 to 10%), Design Development (11 to 35%), and Construction Documents (36 to 100%). The Corps of Engineers limits the phases officially to Concept (0 to 35%) and Final Design (36 to 100%); however, they generally break the process into the three parts. In general, the processes are very similar and major review milestones are at the completion of 10, 35, 60 (for Air Force work) and 95 percent. The review process includes a Biddability, Constructability and Operability (BCO) review, which is conducted by Corps construction and facility operation personnel to minimize problems during bidding, construction, and operation.

The Construction Document process consumes the greatest amount of time and resources, which leaves very little time for the designer to analyze designs, check alternatives, and negotiate conflicts with other design disciplines during the schematic design phase. A constant need exists for reviews and backcheck reviews during the construction document phase. Automating these reviews and moving them forward to the programming and schematic phases would enable the designers to define a better scope for the building program, allow them to check several design alternatives, and provide the time for them to conduct design analysis (energy, life safety, value engineering, roofing systems). Analyses such as these are usually conducted on only large building programs. The ability to move these analyses forward in the process, and to perform them on all building programs, would improve the overall quality of the buildings and the integration of its systems. In proposing a new process to be implemented in the collaborative engineering environment, USACERL took these factors into account.

Format of Design Information Produced

A&E firms and Army Corps of Engineers technical personnel are using CAD systems and related technologies to develop design drawings, conduct engineering analyses, and write specifications used during construction. Many Corps projects must be submitted in CAD format. The web site at the U.S. Army Engineer Waterways Experiment Station (WES) in Vicksburg, MS, has links to the following standards (Tri-Service CADD/GIS Technology Center 97):

- Spatial Data Standards
- AEC CADD Standards (Version 1.4)
- AE Deliverables

- CADD Details
- Productivity Enhancement Utilities for AutoCAD and MicroStation.

Some test projects are even being distributed for bid on CD-ROMs as part of the Electronic Bid Set effort (Tri-Service Solicitation Network 1997). Potential bidders can request the bid set CD-ROM and then print any drawings needed to complete the bid package. They can also use software tools to automate the quantity takeoff procedure. While it takes more effort to save all the drawing and specification files to a CD-ROM for bids, the Corps of Engineers has reduced printing costs significantly. Amendments to the bid set are issued on diskette or via the Internet. (U.S. Army Corps of Engineers 8/14/96) (http://tsn.wes.army.mil/ProjectHomePage.htm).

Current Construction Process

Figure 4 shows the Current Construction Process. Contractors manage and perform construction, while Corps Resident Engineers approve work plans and manage changes and modifications, progress payments, requests for information, construction quality assurance plans, close-out and warranties, and also ensure all as-built information is collected by the contractor. Resident Engineers have a key role in conducting BCO reviews on projects during design. They provide designers with practical construction expertise and lessons learned so that potential problems can be avoided or minimized (USACE 1990).

Format of Construction Information Produced

Even if the project is designed using CAD, most construction personnel are unable to take advantage of the information represented electronically in CAD drawings and databases. The CAD files and databases created during design and documentation are typically printed and used as hardcopy drawings during construction. Unless the construction contract specifically requires the contractor to update the CAD files, the as-built drawings turned over to the owner will be marked up paper drawings. Many Resident Engineers use the Resident Management System (RMS) to support their daily project management tasks (Barker 1991). RMS supports construction management at the Resident Engineer level, including project planning, contract administration, quality assurance, payments, correspondence, submittal register, safety and accident administration, and modification processing and management reporting capabilities (USACE 1993). A decision on deployment of RMS is scheduled for 4th Quarter FY97 (USACE, June 1997, Commander's IRM Smart Book, available to Corps only, in PDF format).

The use of CAD applications and related technologies during construction can result in improved communication between design and construction personnel (Chin 1995). Construction supervisors who have access to CAD drawings and databases could find needed information quickly and easily, and would be able to look at any building section, detail, or work area that was being discussed. This accessibility could help reduce design deficiencies, change orders, and increase productivity, which are affected by problems in communication during design and construction (Stumpf 1994). Construction inspectors would be able to select a building component or performance feature and pull up quality control/quality assurance (QC/QA) checklists if the CAD drawings were associated with relevant databases (Chu 1995). In the future, an object-oriented CAD model of the building could be linked to project control software such as RMS and used to capture and analyze progress information during construction (Stumpf, August 1995).

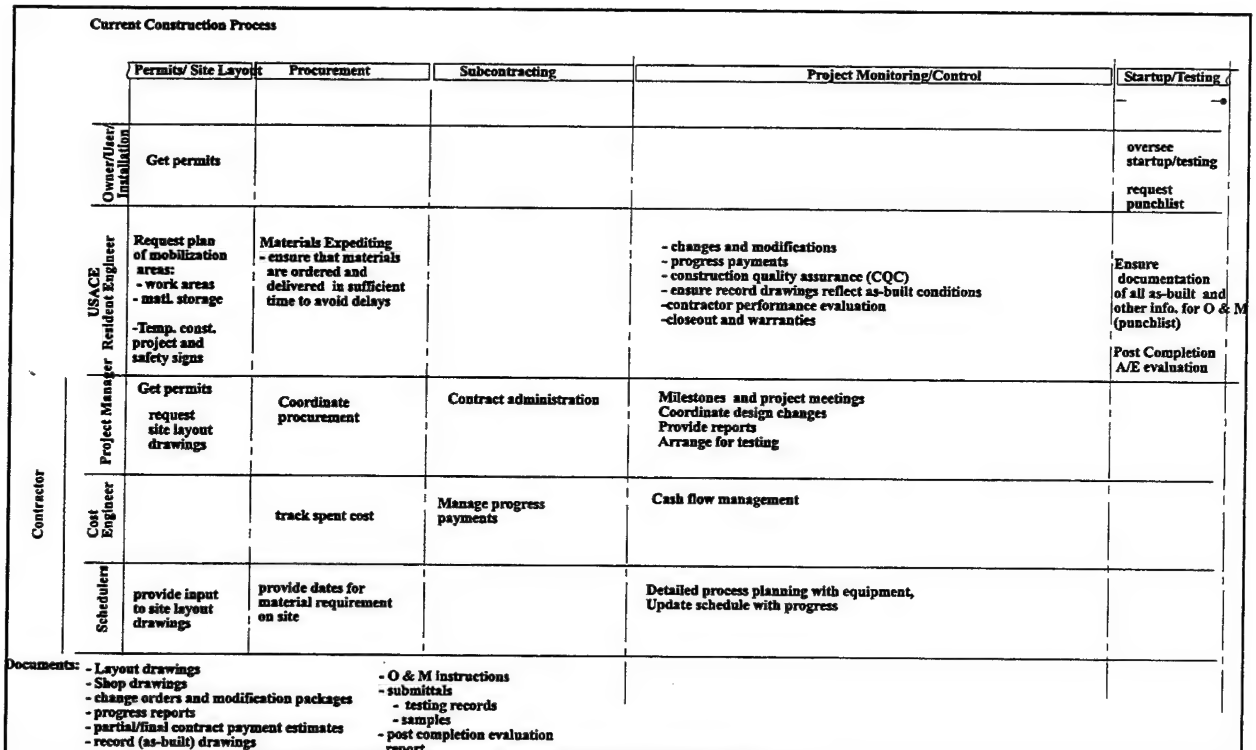

Figure 4. Current construction process.

Accuracy of facility drawings and records required by the using agency, facility manager, and O&M personnel is another area that needs improvement. As-built drawings and building component information are usually transferred to the facility user on paper. Some projects now require that the contractors provide accurate, updated CAD as-built drawings. However, these CAD as-builts are not typically linked to a database of detailed component information. The effective use of CAD or object-oriented CAD technologies to create accurate as-built drawings linked to data on actual building components would provide an electronic representation of the facility which would be useful throughout the life of the facility.

To understand how CE can be used in a reengineered facility design process, a study of the traditional design process was necessary. Focusing on the strengths and weaknesses of both CE and the traditional facility design process, a prototype collaborative design process was developed for experimental purposes.

Using Collaborative Engineering To Support an Improved Facility Design Process

Introduction

The focus of this section will be to document improvements in the facility delivery process that can be gained from the development and use of CE. A facility's life-cycle process usually begins with a requirement for a new building or additional space and ends with demolition or recycle. The traditional A/E/C delivery process consists of several stages: requirements analysis, funding analysis, schematic design, conceptual design, final design, procurement, construction, and O&M. Collaborative engineering is a new way of doing business that uses automation technology to support reengineered A/E/C delivery processes. Collaborative engineering is similar in approach to that of concurrent engineering. Concurrent engineering, mostly used in manufacturing, relies on concurrent or parallel design processes, whereas CE in the A/E/C domain focuses on serial or sequential design processes.

With a CE approach, it is estimated that the Corps' facility delivery time will be decreased by 50 percent and the resulting facilities will be more useful and efficient throughout their life cycle. With CE technology, it will be possible to produce 80 percent of construction documents, save 3 to 9 percent of the construction costs, and reduce facility delivery time from 551 to 115–214 workdays. As a conservative estimate, well-designed buildings will use 25 to 35 percent less

energy for heating and cooling during their life cycle. Technology utilization during the O&M and facility management phase is expected to result in significant savings and improved decisionmaking affecting the $94 billion DOD O&M budget and $14 billion backlog of maintenance. During the construction phase, CE will improve coordination of trades and assist project managers in analysis and optimization of construction schedules. As-built models updated during construction will be used directly by engineered management systems to optimize maintenance funding plans and schedule work costs effectively. CAFMS systems will also be able to use these models to assign space and track inventory. The same models can be reused during retrofit design to modify the use of facilities.

Business Process Reengineering

Hammer and Champy, authors of the much noted *Reengineering the Corporation: A Manifesto for Business Revolution,* define reengineering as "the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical, contemporary measures of performance, such as cost, quality, service and speed." Business process reengineering (BPR) has rapidly developed towards a new management philosophy, based on predecessors like TQM, Overhead Value Analysis, Kanban or Just-In-Time Management. BPR stresses the radical change of processes. However, the redesign of processes is only one aspect of the management of business processes. Dr. Kutschker (1995) writes that at least three different kinds of process management can be identified: the management of ongoing business processes, the improvement of business processes, and the reengineering of business processes.

The management of business processes includes their continuous improvement, but the fact that managers are usually responsible only for functions and departments and not for processes crossing functions or departments hinders this improvement. In most cases, managers isolate parts of a business process by focusing on their department only, which usually results in a suboptimal solution in the improvement of a process (Kutschker 1995).

BPR, as a concept, is valid because it calls for process reevaluation using an analysis that questions both the need for the design and its process. This radical concept is exactly what forces companies to implement it only in a piecemeal approach. The idea of total transformation is abandoned. Although periodic reevaluation and redesign of business processes are valuable managerial and strategic tools, it is not enough with reengineering, which stresses a need to "obliterate" and recreate (Geisler 1996).

Since reengineering involves such a radical change, it is not a tool to be used lightly. Hammer and Champy recommend that organizations apply it at the lowest level of their microprocesses. The basic principles (Kinni 1994) of reengineering that Hammer and Champy recommend are:

1. Organize work around outcomes, not tasks.

2. Design processes that can be accomplished by as few employees as possible.

3. Charge those who will use the output of a process with performing it.

4. Build decisionmaking and internal control into the process.

5. Link parallel activities and perform them concurrently whenever possible.

In the past several years, reengineering fever has swept corporate America, but the vast majority have found that it has not been the magic cure for which they had hoped. Why is reengineering failing to live up to its promise? According to some management experts, managers are to blame. Champy and others contend that the problem is that managers often pay lip service to the effort but are not behind it. They are threatened by the loss of power. They do not display leadership and commitment, do not change their behavior, and do not act as role models. These are some of the reasons that TQM, continuous improvement, and empowerment have failed in many organizations. Mandrish and Schaffer (1996) believe that these are not the reasons reengineering efforts usually do not succeed. They believe the "real problem lies with the essence of the reengineering methodology itself. The radical all-or-nothing approach of reengineering is, for most companies, impractical and unworkable."

When the goal is to dramatically increase process speed, technology will almost always play a pivotal role, but automation is not the goal of reengineering. When deployed strategically, reengineering can fulfill management's short- and long-term goals by redesigning critical core processes, and by synchronizing the organizational, individual, and cultural aspects of operations. "Just as strategy seeks to optimize an organization's response to change, reengineering seeks to understand changing customer needs and wants, and then shape operations to respond to those changes in support of strategy" (Manganelli and Raspa 1995).

New information technologies and automation will have an impact on the coordination of business relations. New technologies such as electronic mail, corporate and public databases, application systems, fax, video and computer-conferencing, are considered to be some of the driving forces of internationalization (Kutschker

1995). Even though the strategic importance of information technology is necessary, few studies closely investigate the relationship between state of the art applications and their impact and importance for coordinating dispersed activities and business processes.

Daniel Burrus (1993) describes how to use technology to go beyond the competition. He discusses 20 core technologies, their relationship to 24 new tools, and 9 ways these tools will revolutionize our lives. The keys to success when reinventing government and business are "anticipation, integration, flexibility, communications and orchestration." He describes how to go beyond the competition by understanding what the new technologies and tools are, and how to revolutionize the delivery system of products and services, the ways in which we communicate, accept and use computers, and internalize, understand and use massive amounts of data. He explains how several companies drastically shortened their design and development process ("leverage time with technology") by using supercomputers and networked computers. Companies need to "enter the communication age," by learning how to collect digital information in a focused and structured way so it is linked to other relevant information. Users would then be able to access information needed to take action.

Blackinston (1996) writes that "In a sense we are emerging from the Dark Ages of U.S. business — the period from 1950-1980 — when managers believed in short-term results, shaving costs, focusing on finance and marketing rather than products and processes, and making deals instead of serving the customer." In the Juran Institute's view, 10 trends have emerged as a result of the TQM effort (Blackinston 1996). One of these trends, Information and Analysis, directly relates to the use of CE in support of the facility design process. The Information and Analysis trend emphasizes measurement and information as key elements of any organization's infrastructure. Information systems are also a key part of the infrastructure of TQM and reengineering. Information can be used to improve the next generation of products, improve business processes, reduce time cycles, improve distribution, improve field service, better understand the needs of customers, and design products and services to meet these needs.

Collaborative Engineering

CE is a new way of doing business that uses information technology to support reengineered A/E/C delivery processes. CE is similar in approach to concurrent engineering (mostly used in the manufacturing area) which relies on concurrent or parallel design processes. CE in the A/E/C domain, however, focuses on serial or sequential design processes. Krajewski and Ritzman (1996) define concurrent

engineering "(or sometimes simultaneous engineering or interactive design), as a process where design engineers, manufacturing specialists, marketers, buyers, and quality specialists work jointly to design the product or service and select the production process." Collaboration involves communication and negotiation between A&E teams at distributed sites as design activities or subtasks are performed. Collaboration technology supports the needed communication. "However, different couplings between subtasks place different demands on the level of communication which must be provided by the collaboration technology of a concurrent engineering environment" (Case and Lu 1996).

Improvements in the facility design, construction, and O&M processes can be achieved through the development of a CE framework that supports distributed virtual engineering teams, intelligent engineering models, and automated capture/reuse of corporate knowledge.

Distributed virtual engineering teams are geographically and organizationally dispersed engineers, architects, and related design professionals working on projects as if they were collocated. Current "web-based" and workflow solutions are essentially advanced document-based management systems that share information in an unstructured way that does not support engineering usage. In other words, the documents can be shared over the network, but the computer has no idea what is in them.

The CAD industry has finally advanced to the point at which it is possible to construct object-oriented models of facilities and it is actively working on object standards for those models (i.e., IAI and Standard for the Exchange of Product Models [STEP]) (IAI 1997). Intelligent engineering models being developed are explicit and computable representations within specific domains that work together to form a comprehensive facility model. These models must be designed to last over the life cycle of a facility, typically 10 to 50 years after construction.

Finally, as collaborative and concurrent engineering become realities, the automatic capture and reuse of A/E/C and O&M information can be incorporated into corporate knowledge bases for use in future designs. With this corporate knowledge, resulting facilities will be more useful and efficient throughout their life cycle.

Change management. One school of change management argues that old practices must be "obliterated" and new processes designed from scratch to fully leverage new technologies and business realities. In practice, few managers have the luxury of redesigning their processes or organizations from a "clean

sheet of paper" — people, equipment, and business knowledge cannot be so easily scrapped. However, some types of organizational change are riskier if undertaken piecemeal or incrementally. Change managers do not always recognize interdependencies among technology, practice, and strategy (Brynjolfsson, Renshaw, and Alstyne, 1997). "Downsizing is an American reality" (Hubiak and O'Donnel 1997). The underlying assumption forcing the need for downsizing is the belief that there are excess jobs within the organization and that elimination of these jobs will improve the organization's effectiveness and efficiency without hindering its competitive advantage. Hubiak and O'Donnell (1997) say that over 8 million people lost their jobs to downsizing in U.S. organizations between 1980 and 1993. Layoffs averaged 3,106 persons per day in 1994 and, although reductions slowed somewhat during 1995 and 1996, many large organizations such as AT&T, Boeing, and BellSouth are still cutting back.

Reengineering is not easy, inexpensive, or speedy. Hammer and Champy wrote that reengineering an entire corporation can be a 10-yr process, which is why a commonly quoted statistic states that 70 percent of reengineering efforts fail within 5 years (Kinni 1994). Hammer and Champy are now stressing several key ideas.

> First, reengineering is done in a deep cultural context, those things an organization values, believes and rewards. Second, more attention must be paid to the issue of people. The changing covenant with workers means that if an organization can do more with less, even a good worker may be let go. Last, when an enterprise reengineers, it becomes *more* people-intensive, not less — a realization at cross-purposes with the old idea of automation as worker reduction. Reengineering gives workers accountability, thus increasing an organization's dependability on people (Ettorre 1995).

Steven Kensinger (1996) wrote "When studying the volumes of books by management gurus, engineering and the design process are conspicuous by their absence." Most business experts focus on general business processes. Kensinger describes the design engineering process as a unique race similar to an endurance run through an uncharted obstacle course. Successful design teams have most of the key elements for success: elements of cross-functional teamwork, agreeing to disagree, hands-on approaches, spending time with customers, tolerance of failure, and following the product from birth to death. When the informal communication and cooperation networks, which are vital to performing engineering tasks, are disturbed during restructuring, product development is affected. (This effect was described in Doron Levin's book, *Irreconcilable Differences*.) The early introduction of computer tools left some designers struggling to figure out the technology while still doing their regular jobs. As designers learned how to use computer tools, a new design process emerged based on the computer tools rather than the product requirements. To achieve

the true potential of computer-based engineering tools, Kensinger stresses that a technology-assisted design process can be built that uses computer tools while allowing the user to focus on the product being designed.

Therefore, the premise behind the development of computer-based engineering tools, that automation and technology can replace the downsized and reduced resources in DOD is, according to Hammer and Champy, a fallacy. DOD may end up depending more on their people. So what is the alternative? One way, as recommended by Mandrish and Schaffer (1996), is through *results-driven process redesign*.

Results-driven process redesign. The results-driven process redesign approach uses many elements of reengineering, but blends them into a continuous improvement approach. The foundation of this approach is to redesign the process: (1) with a focus on results, (2) in a way that involves all the key players in the redesign process, and (3) incrementally, rather than attempting to redesign everything at once. This approach, along with the use of CE techniques, is most likely the best approach to improving the facility design process. The foundation of the facility design process is too large and involves too many legacy processes to totally reengineer.

The seven steps (Mandrish and Schaffer 1996) involved in the results-driven process redesign are:

1. Identify the most urgent business performance improvements needed by the organization, and be clear on the specific improvement in results that are needed.

2. Identify the one or two business processes that most need to be changed to help achieve the key performance improvements.

3. Identify all the key stakeholders in the process, including those whose jobs will likely change as a result of a redesign.

4. Form a team from among these stakeholder groups and give the team the assignment to not just make recommendations but to actually implement changes immediately that will achieve the desired results.

5. Have the team work quickly to: gather any required data, map the process, design the needed improvements that will meet the goal, and get the necessary input or approvals to enable action to be launched.

6. Implement the changes.

7. Monitor implementation and results, and introduce supporting changes in systems or infrastructure as needed. Then use the initial successes as learning experiences for launching the next wave of process redesign efforts.

Substantial savings could be realized by placing more emphasis on optimizing the facility design process. A fully implemented collaborative software environment could significantly improve the quality of decisionmaking, contract documentation, and related micro-design processes. Through collaborative technology, extended design groups work as a coordinated team, and software assists designers in making optimal decisions through improved information dissemination and conflict management. Designers have the capability to effectively consider a wider variety of design solutions and evaluate additional alternatives to improve the quality, constructibility, energy efficiency, and life-cycle cost effectiveness of the facility. Improved communications via the Internet and CE environments can enable interdisciplinary multi-organizational design teams to effectively collaborate throughout the facility design, construction, and use of a building.

Reengineered Design Process in a CE Environment

The following proposed reengineered facility design process (Figure 5) demonstrates how improved information-sharing capabilities and conflict management during collaborative design enables a team to resolve design issues and conflicts earlier in design development. This sharing of information could result in an improved facility design, fewer errors and omissions, and better interdisciplinary coordination of design goals and building systems. Figure 5 shows how design information evolves in the testbed's CE environment.

Information Evolution in a CE Environment

Figure 5 also shows how design information evolves in the testbed's CE environment. The Expanding Facility Model illustrates how a building's design information increases throughout the process of design. Once the facility is handed over to the owner the facility model becomes Corporate Knowledge. This knowledge can be used for future designs, operations and maintenance activities, and building management.

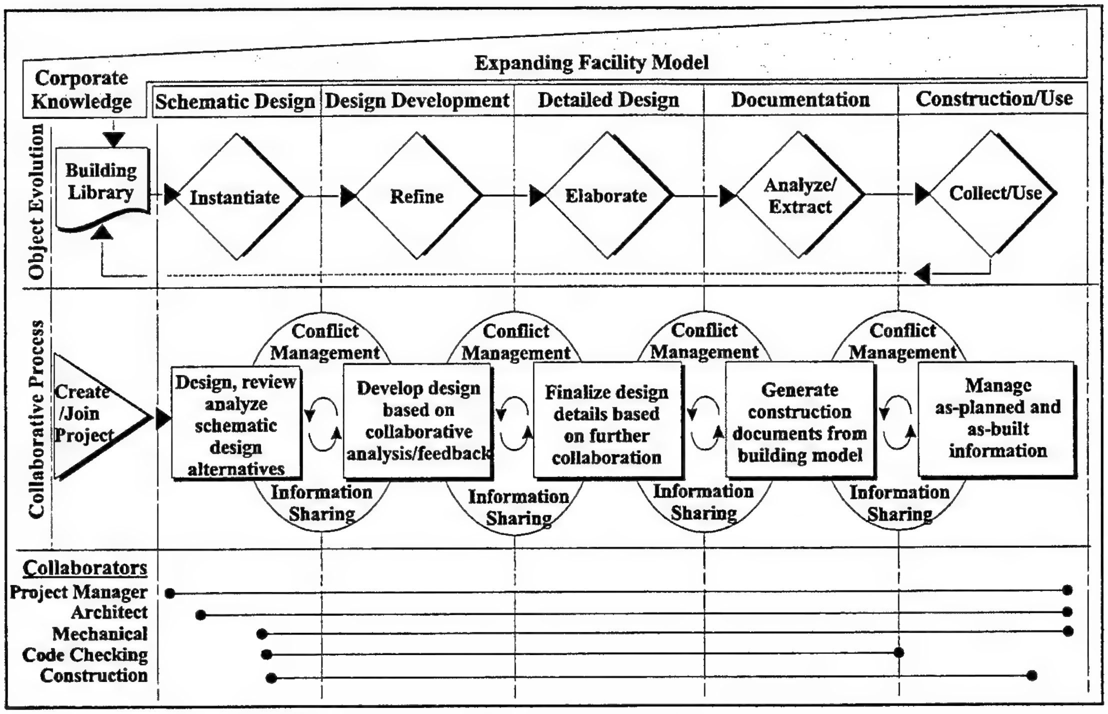

Figure 5. Design information evolution in a CE environment.

Instead of following the traditional design process, the evolution process emphasizes how the documentation stage of design can be reduced to allow more time for design development and detailed design. Conflict management and information sharing during these earlier design stages reduce changes in the documentation and construction stages. The reduction of changes and modification during construction can greatly reduce the time and cost of construction.

As shown in Figure 5, throughout the different stages of design, design information evolves, increasing the size of the facility model. During the schematic design stage, designers pull design information from corporate knowledge and the building library and *instantiate* or create their new design. Once the design reaches a certain stage and the designers would like analysis and feedback from other project participants, they can broadcast and receive each other's design information. While in the design development stage, design information is being *refined* or further analyzed. Detailed design requires designers to *elaborate* and finalize their design. Documentation is expedited by developing documentation standards which can be *analyzed* and used to *extract* information during the automatic generation of construction documents (Griffith 1996). During construction and occupancy, the facility design information can be *collected* and *used* to manage the as-planned and as-built facility model (Brucker and Stumpf 1996).

3 Testbed Technology

The testbed supports teaming by using a distributed object-oriented database, called the Virtual Workspace System (VWS) (Heckel et al. 1997). The Agent Collaboration Environment (ACE) uses VWS to broadcast changes to shared design information (centered upon an object-oriented representation) between team members. The information exchange between these two systems is accomplished using Virtual Workspace Language (VWL), which incorporates the Knowledge Interchange Format (KIF) and the Knowledge Query and Manipulation Language (KQML).

The testbed uses a virtual teaming architecture centered around a distributed object-oriented representation of the design and process information. A testbed library representation has been developed to provide a shared set of concepts (ontology) which facilitates the creation of objects and communication of information. This representation contains both product and process information. By providing process information, this representation allows sophisticated project management and the development of construction plans. Agents that use this shared representation have been developed for project management, architectural layout, code checking, mechanical/energy analysis, construction planning, roof design, and O&M. Legacy tools such as CAD have also been integrated into the system. The following sections describe the components of the testbed demonstration which enable the creation, manipulation, utilization, and communication of information about a facility design.

Agent Collaboration Environment

An agent-based software environment developed at USACERL, ACE is specifically designed to support the delivery and sustainment of facilities (Hoff 1995). Concurrent Persistent ACE (CPACE) is a C++ version of ACE based on a commercially available object-oriented database (McGraw, June 1996).

Agents are expert systems that are tightly integrated with each other using libraries of objects such as walls, fans, or pumps. Agent-based systems are well suited for use as integration platforms. Complex systems can be gradually

implemented using many small agents, making the system easy to maintain since agents may be changed internally or replaced without affecting the remaining agents. Although most agents act under the user's direction, they can also run in the background and act in an advisory capacity.

The primary role of an agent in ACE is as an assistant that uses heuristic rules and a powerful checklist facility to automate routine tasks, thus enhancing productivity and ensuring repeatable work process quality. Experienced users can store their knowledge in agents for use by others. The true strength of ACE, however, is tool integration. ACE offers the possibility of blurring the distinction between data in CAD drawings, analysis programs, and contract specifications. It makes this integration possible by providing a central database that reduces redundant data input and the associated risk of human error, thus improving document consistency. ACE supports the Discourse Model of collaboration (Case 1996). Artifacts in ACE take the form of frames, generalized semantic links, and constraints, described below.

Frames

Frames describe the data structures and behavior of system components being designed, whether physical or abstract. In the architectural domain, examples include walls, windows, and ductwork. When a frame is instantiated, it is often referred to as an instance. Definitions of frames are obtained from a frame library that may be shared by a group.

Semantic Links

Semantic links represent relationships between frame instances. For example, a wall that includes a door would represent that relationship by a has-part semantic link between the wall instance and the door instance.

Constraints

A constraint is used to build and enforce mathematical and symbolic relationships between slots of instances, based on a model used by Steele (1980). For example, a constraint can be used to require that a wall outlet be located 0.5 m from a door. They are also used to detect conflicts between users. For example, if a user has an opinion that a window should use glass with low emissivity, that opinion would be represented by attaching a constraint to the type slot of that window, annotated with information about the user and agent that hold that opinion. When several slots are connected in series by constraints, values will

spread through a network. This capability makes ACE well suited for parametric design.

The Discourse Model supported by ACE uses knowledge-level agents (Genesereth 1988) that manipulate artifacts in a workspace. An agent represents the user during the design process by manipulating or reacting to artifacts present in the design context. In fact, human users are not allowed to directly manipulate the workspace. Instead, a special user agent must be provided by the workspace to act for the human user.

Library Representation

A common library for the electronic modeling of product and process information has been developed to provide a shared ontology with which all participants can create objects and communicate information.

The common library representation is the most critical component of the collaboration scenario, which was defined as a heterogeneous, closely coupled (participants working closely together) environment. Therefore, the ontology about which communication is centered must have fixed communal definitions. As part of the demonstration exercise, a vocabulary was developed that was sufficient to communicate the contents of preliminary design. This vocabulary contained objects, slots, facets, values, type, and object inheritance. Semantic relationships defined in the library consisted of only "part-of" and "is-a" relationships. It was the developers' intent to have a minimum set of definitions within the library representation.

By using the common library representation, heterogeneous agents communicated about objects on a one-to-one relationship. No translation was required during communication. For example, when the architectural agent talks about doors, the O&M agent understands exactly the same meaning for doors. By working from a common library representation, a major hurdle in communication was overcome by removing ambiguity in the meaning of concepts.

The ontology provided by the representation included concepts from each of the disciplines in the demonstration. Therefore, the representation included descriptions of architectural zones, building components, construction time and cost components, and functional requirements. Libraries of frames mimicking the common library representation were created in the ACE environment. Using these libraries, participants in the demonstration could create instances of the frames and could share this information with other users. Other participants

receiving this data could understand the content of the information because their libraries would be identical to the one in which the object was originally created.

ACE Interface to Computer Aided Drafting Tools

When large amounts of data exist (which is usually the case in the facility delivery process), it is essential that this information be displayed in a graphical manner (Sriram 1992). Therefore, an important element of the ACE system is its ability to graphically represent objects that are defined in a shared library of frames. CAD tools can be used to display the objects. The ability to communicate with CAD systems is referred to as a "CAD interface." ACE presently has CAD interfaces using AutoCAD Release 12 for Microsoft Windows and Microstation 5.0 for the Microsoft NT environment. The CAD interface provides a two-way link from the product model representation in ACE to a graphical representation in CAD. Groups of lines and arcs can be displayed in a CAD drawing to represent individual instances of data in ACE. The CAD interface has a mechanism for changes made in the CAD drawing to be automatically reflected in the associated ACE objects. Likewise, if a user edits an ACE object directly, the rendering can be redrawn to reflect these changes.

The CAD interface is implemented at the base level using Microsoft's Dynamic-Data Exchange (DDE) technology, which allows communication links to be established between separate applications running in Microsoft Windows or NT. Once a link is established, messages containing strings of information can be exchanged. With the CAD interface, messages are passed through a link created between ACE and the CAD system. A message consists of a "packet" of information and contains an operator, sequence number, and data element. A message packet is sent to CAD from ACE, is then decoded and evaluated in the CAD system, and the result is returned to ACE in an encoded message packet.

With the base message-passing link in place, the system must now allow the user to specify how instances of frames in the shared frame libraries should be drawn in CAD. To accomplish this, drawing routines are written and stored with the ACE frames. These routines call CAD drawing functions in order to cause a shape to be drawn in a rendering. When such a routine is called, the CAD system returns a unique identifier for the drawn shape. This identifier is stored with the associated instance in ACE. In a similar manner, the ACE object sends a unique identifier (e.g., its instance name) that is stored with the associated CAD object. The completion of these two steps creates a two-way link between both objects. Much of the coding required to make "CAD-aware" objects has been

implemented into standard CAD shape object definitions. A user can create new frames that inherit from existing frames and have all the code necessary for graphical representation.

With the two-way link established, a menu- or icon-driven user interface has been created to be used in the CAD system. This user interface can be used to create or modify CAD-aware objects from within CAD. It is then possible to use native CAD commands, such as the "move" command, to manipulate CAD-aware objects and still maintain consistency in the two representations.

Virtual Workspace Language

The information exchange between applications in the two previously described systems is accomplished using the VWL protocol, which is used for communication between programs having disparate representations. The VWL protocol incorporates KIF and KQML. KQML performatives describe messages concerning information or knowledge being communicated from one program to another.

Using the Discourse Model, the individual workspaces used by each human user of ACE are joined into VWS, which supports asynchronous and distributed collaboration. Although users are working in ACE on their own computers, in effect there appears to be one large workspace. A set of workspaces joined in a VWS is called a group. Each workspace in the group is uniquely identified by a *userid* code, which is associated with the human user of the workspace.

Workspaces communicate using an electronic mail system called VWS-Mail. The rationale for using a mail system analogy is to provide message-store capabilities so that a workspace can send a message to another workspace with the assurance that if the other is not on-line, the message will be stored until accessed. Message-store permits a group member to isolate a computer from the network for a period of time, work on the design (or perhaps travel), and then reconnect the computer to the group and receive updated information.

Workspaces communicate with each other by formulating and sending messages in VWL, which is intended to be used by programs conforming to the Discourse Model. VWL uses KQML performatives to send messages (Finin 1994). Its principal verbs are: interest, shadow, link, constrain, conflict, and rationale. For more information about VWL, see Case (1994).

Integration With Commercial/Legacy Software Tools

Architects, engineers, and others who are involved in the facility delivery process use commercial and legacy (corporate information management systems) software tools to help them accomplish their design and analysis tasks. USACERL used ACE to integrate the following software tools within the agents, which were developed to support design and analysis tasks:

- Microsoft® Project for Windows©
- Microsoft® Excel for Windows©
- BLAST (BLAST Support Office, 1994)
- MCACES® (MCA Cost Estimating System) (Building Systems Design, Inc. 1992).

Software Agent Defined

Software agents are expert systems that are tightly integrated with an object-oriented database, traditional CAD, and other engineering tools. In conjunction with the database, agents are the glue that integrates various applications in a coordinated design environment, and they provide a repository for consistent facility modeling. These systems have several unique features, including: rules that capture design knowledge, constraints that allow logical connections between related design objects, and design rationale for decisions made by either the designer or agent. They are also opportunistic—if any information is changed, added, or deleted, they determine how the agent's "viewpoint" is impacted and respond appropriately. Agents can automatically generate many types of construction documents with consistency and without the common errors found using existing CAD systems.

The term "agent" used loosely can mean any piece of software (software agents) or person (user agents) that can possibly affect change to electronic data and/or interact with other agents (Kautz et al. 1994). Software agents are software systems that operate within an electronic environment, which can sense the state of and affect changes to this environment. For the sake of brevity, only the software agents used in the testbed demonstration will be discussed in the following chapters. A software agent usually consists of a set of rules that are used to diagnose a problem, check for errors, or otherwise automate a task. In ACE, software agents are miniature expert systems that can aide a user in

performing his or her normal duties. These ACE agents consist of rule-bases and/or checklists that step users through plans to be executed, thereby allowing the user to control the manner in which the agent performs work.

4 Testbed Scenario

Approach

CE Testbed Scenario

Figure 6 shows the key collaborative engineering principles that the testbed demonstrates: intelligent agents, information sharing, and conflict management. The figure shows the participating agents involved in the schematic design phase, software tools used, design interests, conflicting interdisciplinary viewpoints, and the impact these could have on the design process.

Current Participants and Software Agents

Project Manager

The project manager agent has two major responsibilities: providing site information to all pertinent project members and managing project coordination, project scheduling, and resource allocation. Some of the information created by the project manager includes project team members, project milestone information, site benchmarks, site contour information, project budget and duration, and soils information.

Architectural Layout

The architectural agent enables the architect to input a functional hierarchy of the building program into ACE. Starting with a building object, semantic links can be developed between building components. These building components are then placed in a CAD system using the CAD Linkage. For example, walls are automatically generated from room coordinates.

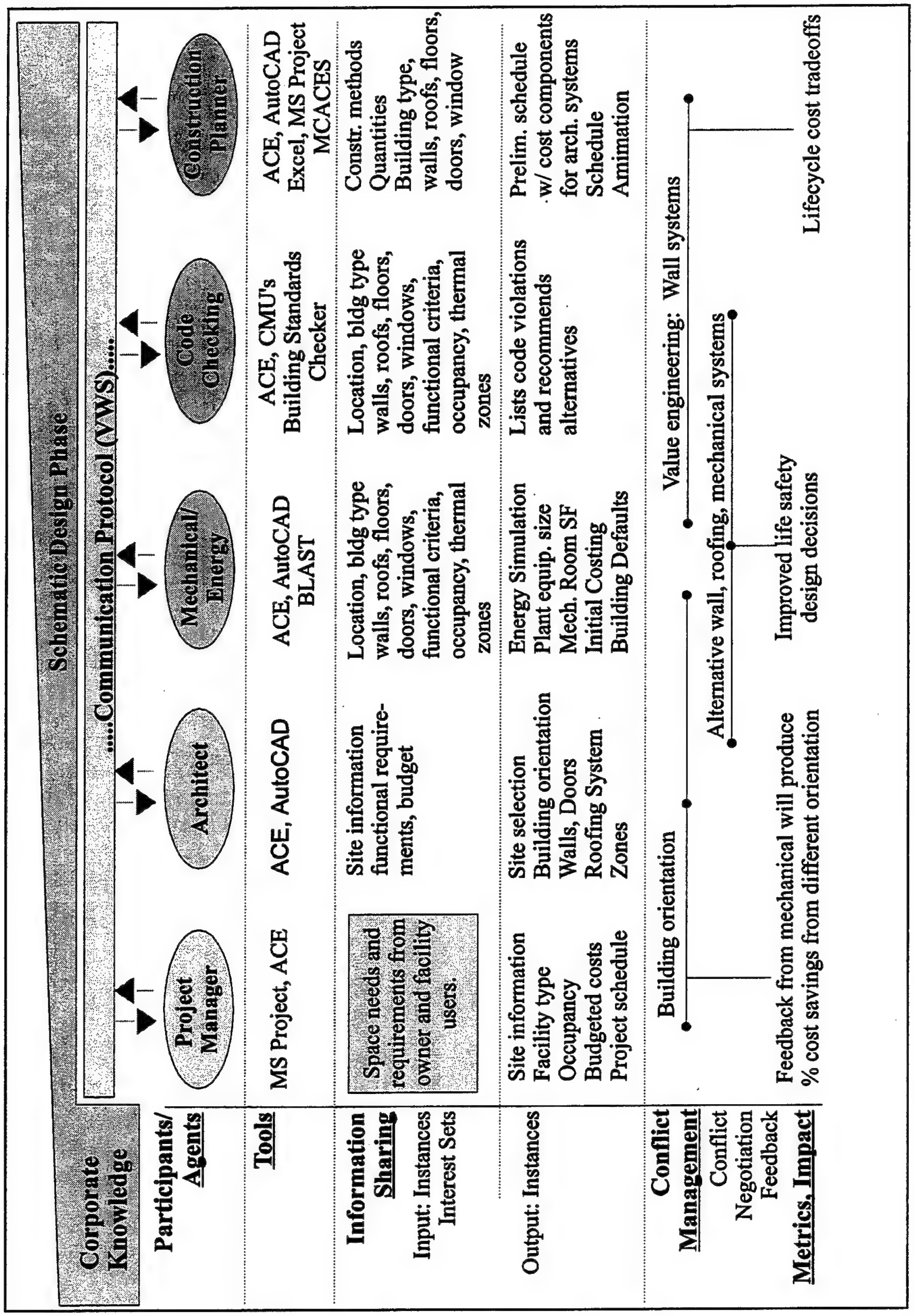

Figure 6. Collaborative Engineering testbed scenario.

Early Cost Estimating

Develop cost estimates at the programming stage of design when the building is completely programmed. The purpose of developing an estimate is to confirm any previously established tentative budget. Assumptions are made about the size and form of the building and the building systems to be used. Also, provide a capability to compare costs of alternative building systems in the conceptual design stage.

Code Checking

Carnegie Mellon University has developed a Building Standards Processor to support the processing of formally represented building codes and standards during the preliminary design of buildings. A module was developed to facilitate communication between CMU's Standards Processor and the testbed demonstration project (Hakim 1993).

Mechanical/Energy

The mechanical/energy agent is concerned with the energy performance of the facility. At the earliest possible stage, an agent conducts an analysis of the thermal behavior of the facility and recommends changes to improve the thermal performance. A thermal simulation using BLAST is performed so that proper equipment type, size, and control can be determined. The simulation results provide information for life-cycle costing, and selection of fan system, coils, and plant equipment (Pedersen 1995).

Construction Planning

The construction representative is concerned with the facility's constructibility. At the earliest possible stage, the agent generates a preliminary cost and schedule for facility designs to compare alternative designs from a construction time and cost perspective. Before actual construction begins, the agent can animate the schedule to verify it and to identify constructibility problems and correct them. The agent can provide a good baseline schedule and cost estimate for evaluation of contractor bids, and also determine the impact on schedule and costs due to change orders and modifications during the construction management phase (Ganeshan 1995).

Roof Design

The Support Environment for Design and Review (SEDAR) for flat and low-slope roofs helps prevent errors during roof design by graphically marking areas on the design off-limits for a selected design object. SEDAR also notifies the designer as soon as an error is detected, with the intent of reducing the possibility of extensive redesign. Finally, SEDAR allows designers to seamlessly integrate reviews based on building subsystems with the design process. A hierarchically-decomposed, task-based model of an experienced designer, the Designer's Task Model (DTM) was developed for flexible control of the operation of an expert critiquing system (Fu 1996).

5 Testbed Demonstration

Once the PM has performed his/her responsibilities, the AR begins by placing rooms creating a space layout plan. At this point the design is still a two dimensional drawing. From here, the AR uses the *expand room* command to create the three-dimensional object drawing (Figure 7).

This command automatically places wall, floor, and ceiling objects that are semantically linked to the original space. Once the rooms have been converted to three-dimensional spaces, the architect begins further development of the plan by the addition of doors, windows, roofs, and foundations. These items are essential to the collaboration between the AR and the ME.

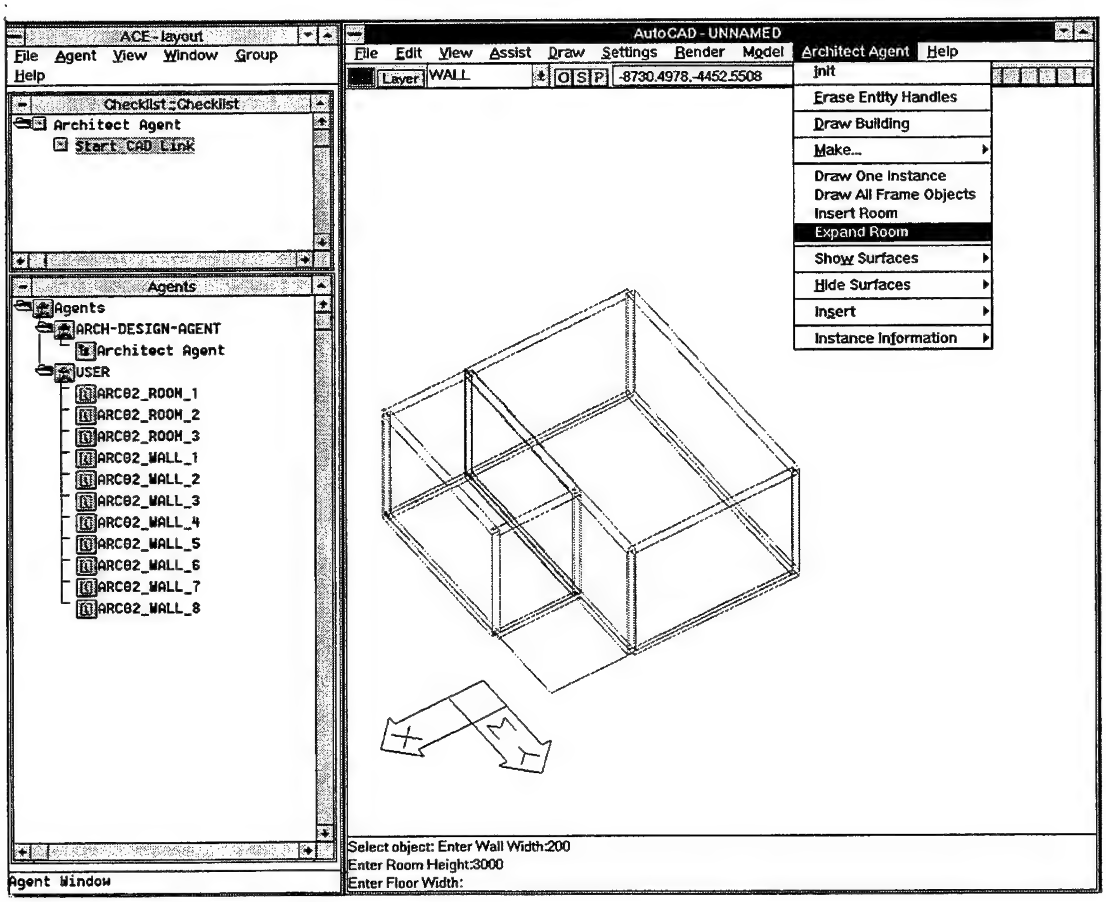

Figure 7. Inserting rooms and expanding walls.

During this development, it is essential to gain crucial design information from all parties involved. For example, an ME will show his interest set by sending a message to the AR through the VWS protocol. Once the AR has received this information, he/she broadcasts the object model based on the information sent from the ME.

Once the ME has received the interests from the AR, he/she can proceed with creating thermal zones (Figure 8) and running a BLAST simulation. After the program has been run, the ME can view the results in VB graphics to determine where problems may arise in terms of too much air infiltration or other items which may cause the building to become energy inefficient (Figure 9).

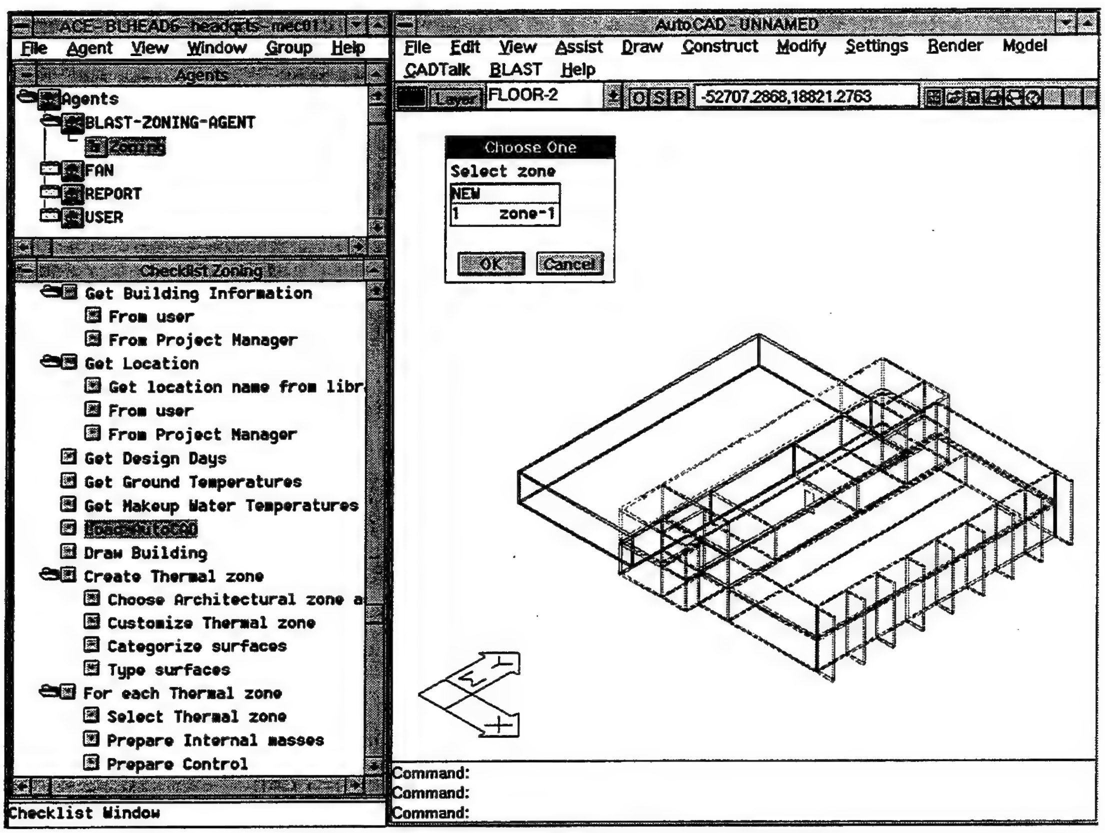

Figure 8. Creating a thermal zone.

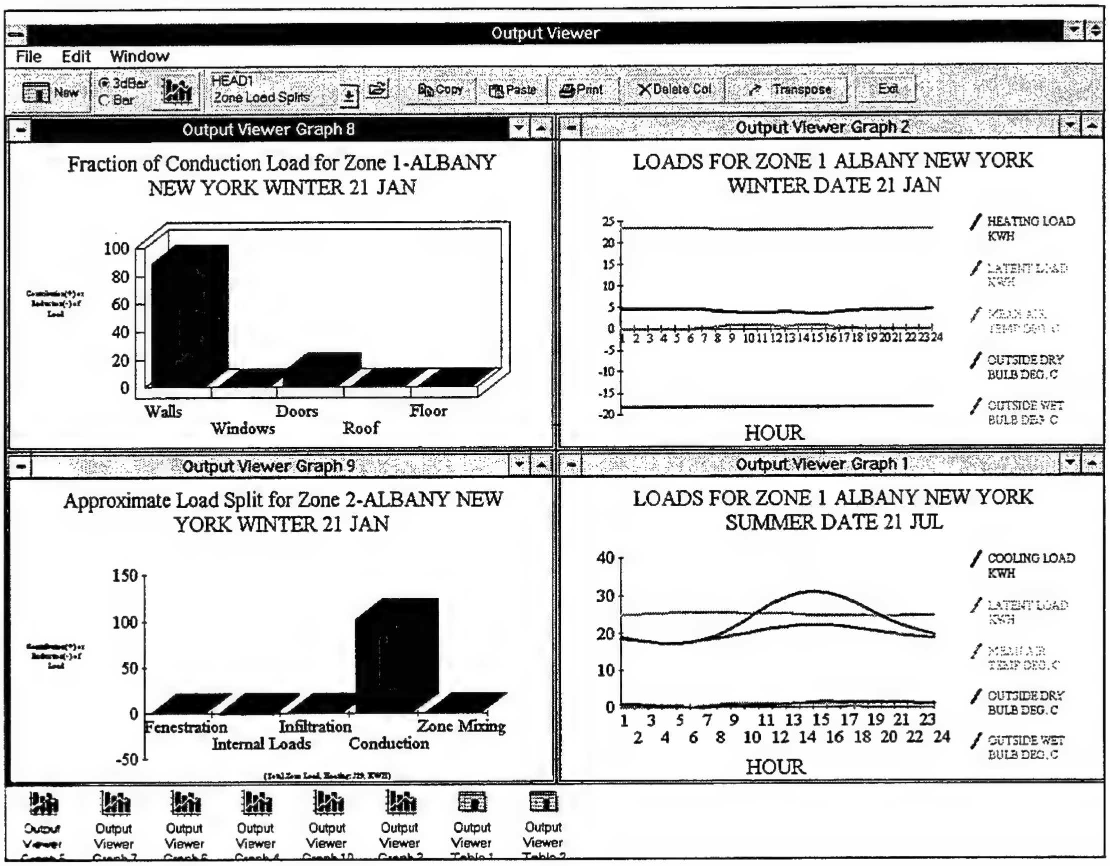

Figure 9. Review BLAST simulation results.

At this point, the ME notices that, if a certain window's properties are changed, then the results of the program would be much different. To try to help alleviate the problem, the ME alters the size of a window, which causes a constraint violation to arise between the ME and the AR (Figure 10).

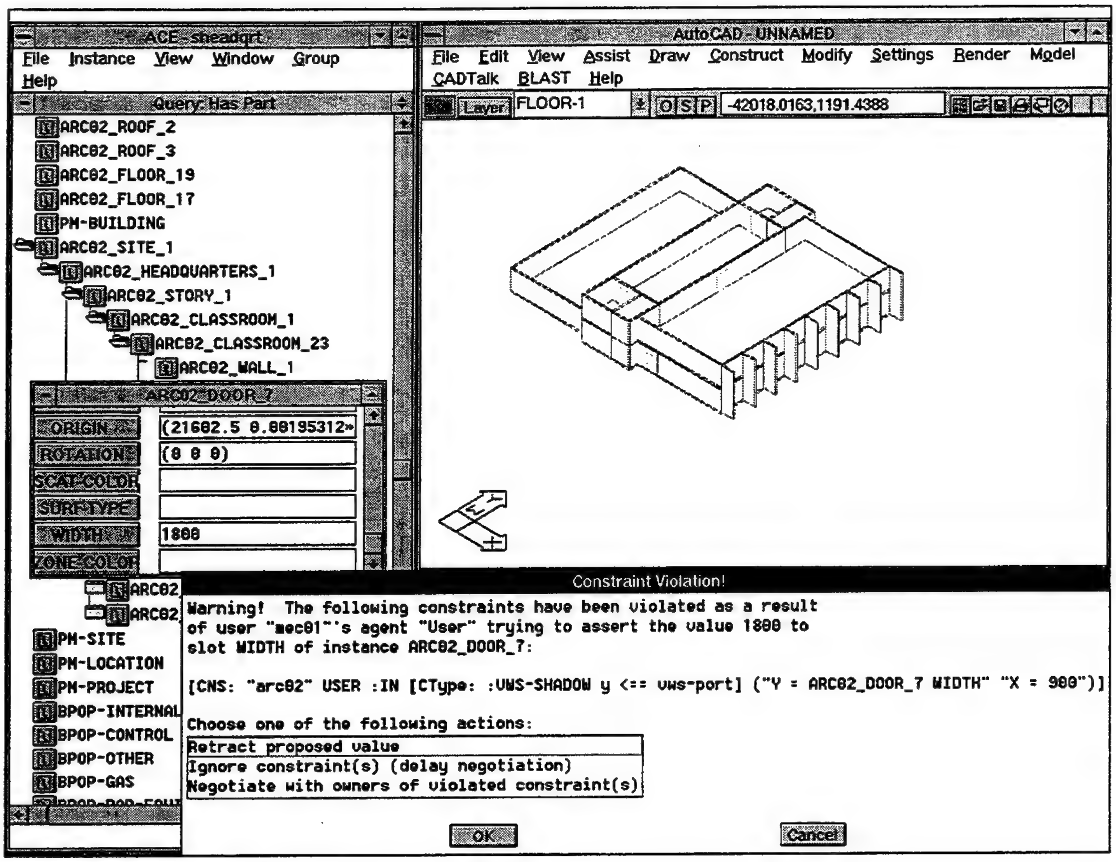

Figure 10. Constraint violation.

Through VWS, the AR notices the conflict and proceeds to negotiate with the ME by choosing which conflict to negotiate (if more than one exists).

Once the conflict to resolve is chosen (Figure 11), the AR begins to resolve the conflict with the ME through videoconference, telephone, or e-mail (Figure 12).

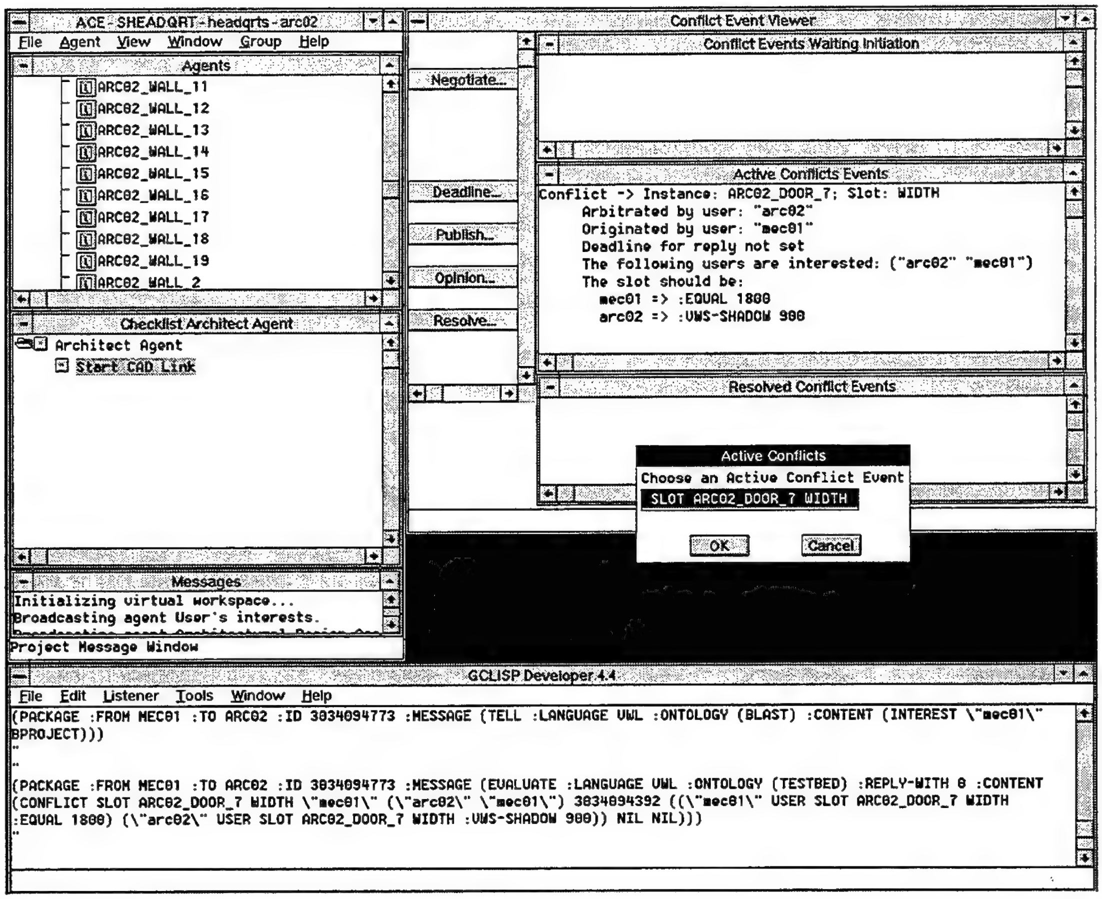

Figure 11. Choosing a conflict to negotiate.

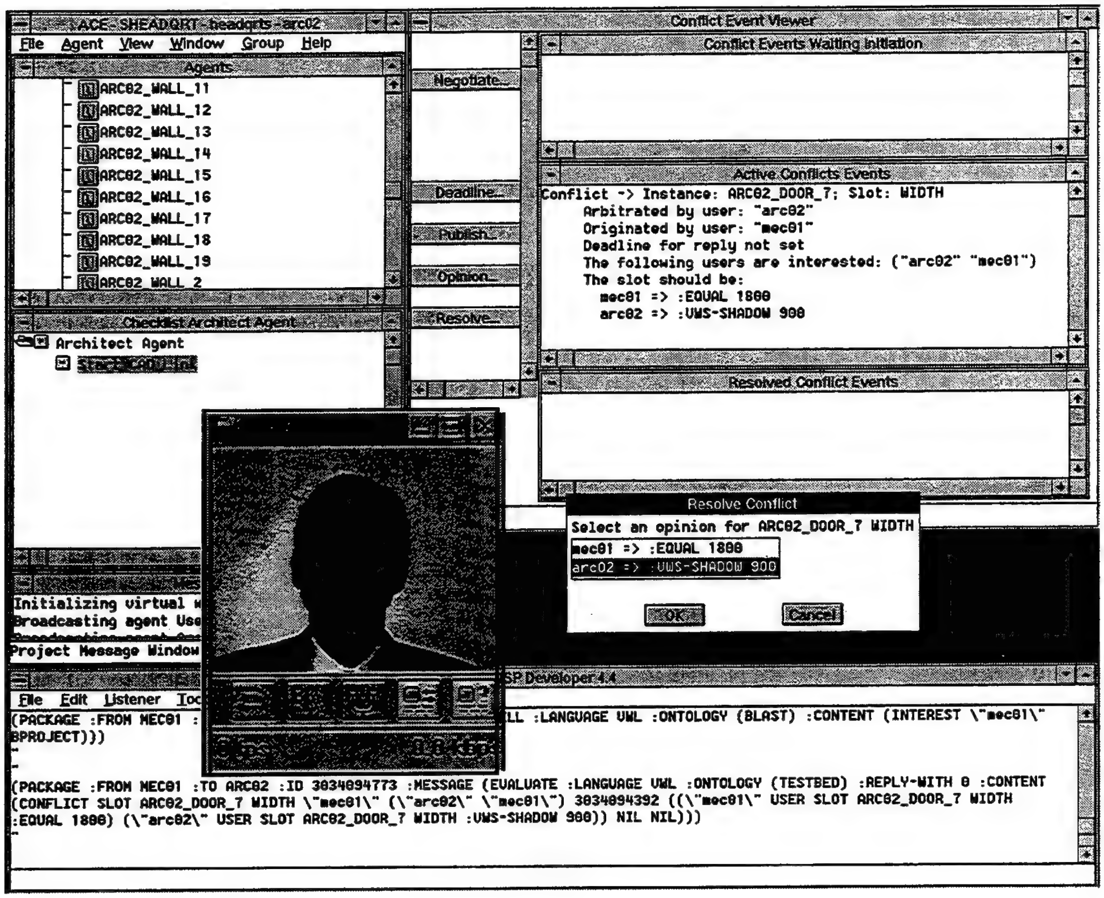

Figure 12. Resolving the conflict.

Once the conflict has been resolved, both parties can view the results on their computers (Figure 13) and continue with resolving more conflicts or continue with the design process.

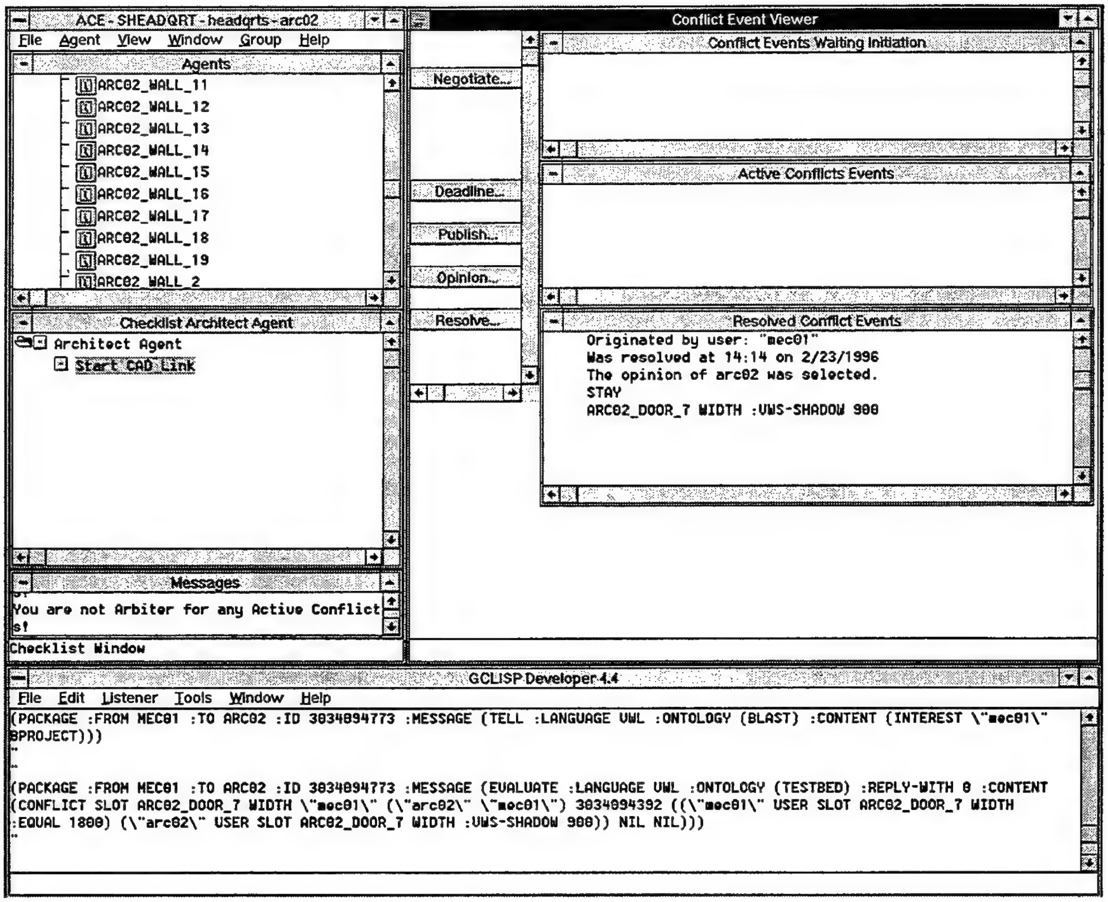

Figure 13. Viewing resolved conflicts.

Once the mechanical design has been completed, the process continues with the roofing design. The designer, who is only interested in the perimeter structure, will send his/her interest set to the AR and will broadcast his/her object model to the roofing designer. After the perimeter structure objects are received by the roof designer, he/she can proceed to design by placing objects on the roof design (Figure 14).

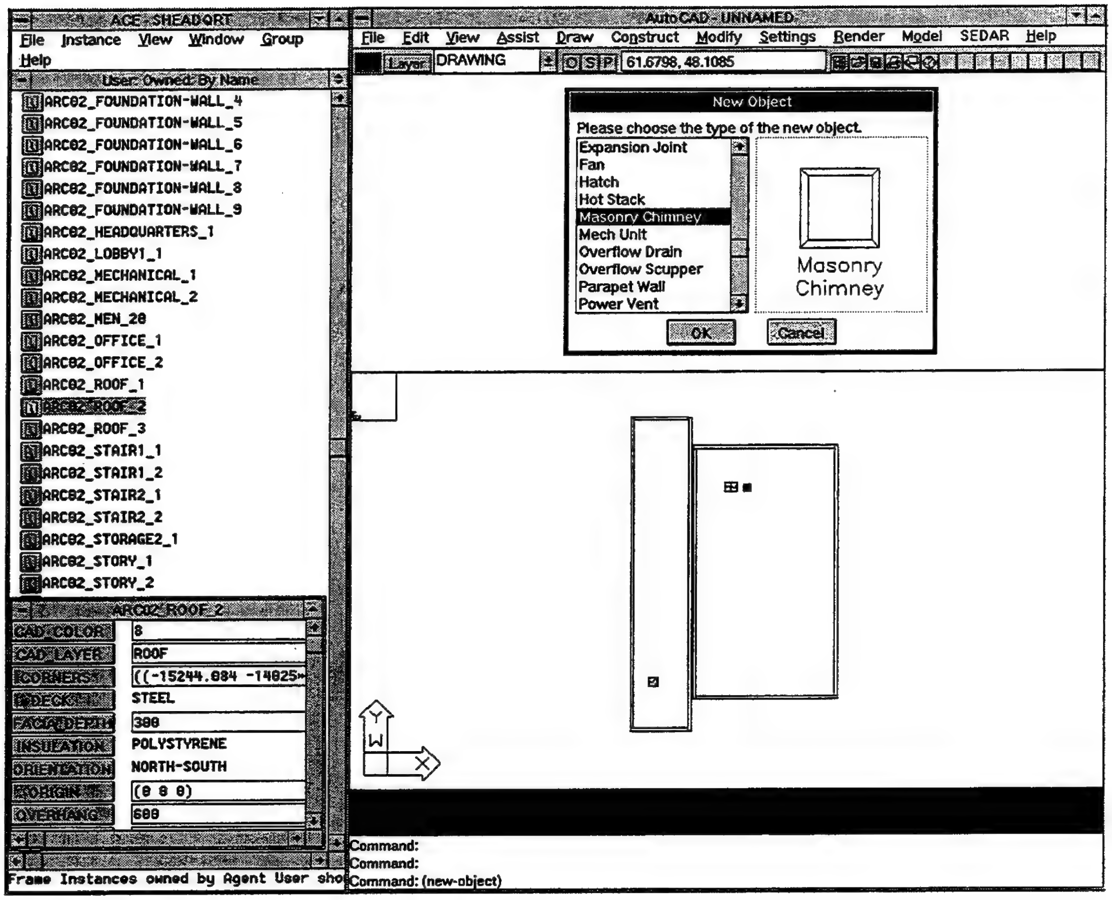

Figure 14. Placing a new object on the roof design.

After the roofing design has been completed, it is time for the construction planner to become involved in the process. The planner will similarly send his/her interest set to the AR, who will broadcast the object model.

Once the planner has received the interests, he/she will begin by developing the building systems components (Figure 15).

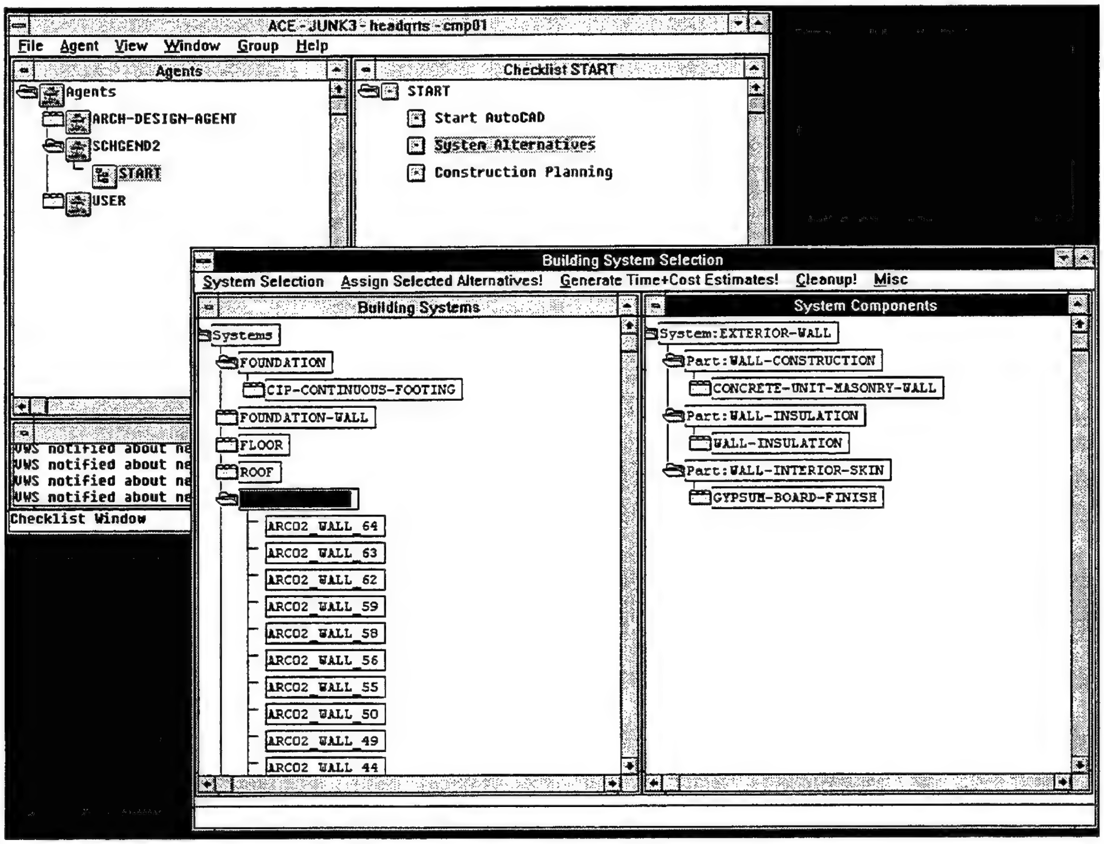

Figure 15. Assigning building system alternatives.

Once building system development is completed, the planner can continue the process by creating a preliminary schedule for the project. This schedule helps in the initial design by determining where delays will occur and can allow time for the resolution of these problems before they occur (Figure 16).

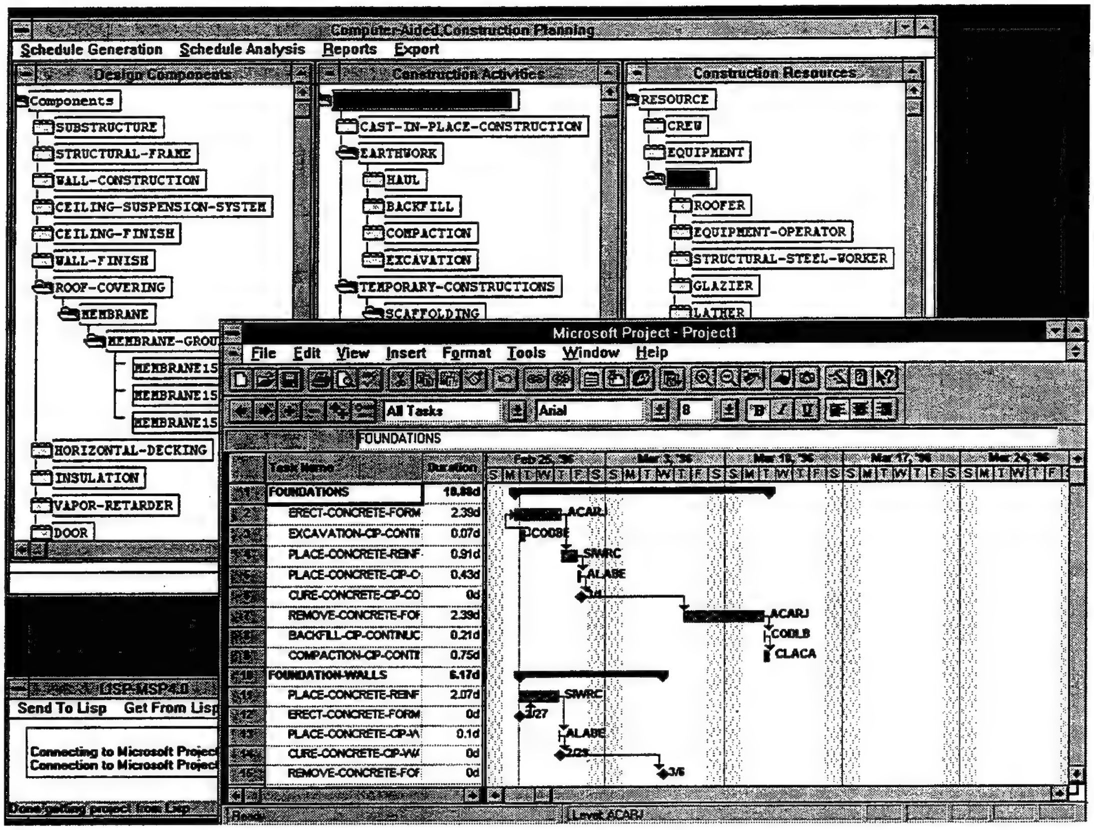

Figure 16. Project schedule generation and sequencing.

In addition to showing the construction process simply by timeline, the construction planner can demonstrate the construction process visually through computer animation (Figure 17).

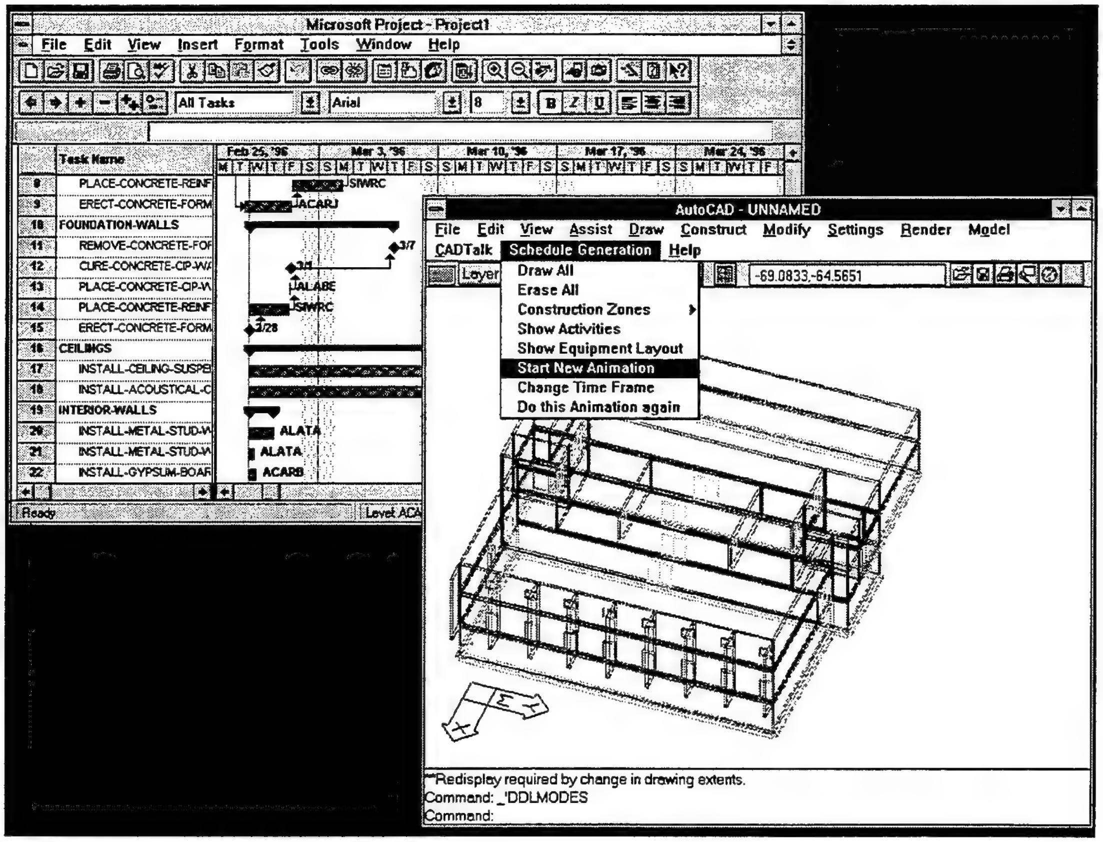

Figure 17. Construction animation.

After all parties have participated in the preliminary design, the process starts all over again. The AR will take all the information generated and use this information to help better the design and resolve problems to create a more efficient facility.

6 Summary

Lessons Learned

Working on the testbed project was a productive experiment in collaboration. Not only did the researchers have to agree on a vision of what the testbed goals were, they also had to agree on how the shared object-oriented facility model should be represented, and how the software agents should work together. It was discovered that a large facility model was difficult to work with within the ACE environment. The testbed software did not scale well for large models.

The architectural design process using three-dimensional (3-D) objects is different than the traditional design process. The designer using new design tools is working in 3-D space, using 3-D objects, while the designer using traditional tools may still be thinking in two dimensions for doing layouts, elevations, and section sketches, then switching to 3-D to do renderings. The designer using traditional CADD tools or paper and pencil uses an implicit representation of the design artifacts. For example, a line may represent a wall of an undetermined type. When designing with object-oriented tools, the designer selects a wall object and inserts it into an explicit representation of the design — a 3-D model of the facility being designed. Since a design represented implicitly is subject to interpretation, much of the design information is subject to the viewer's imagination. Two people viewing the same design may think the same line represents a different item. A 3-D model represented explicitly would mean the same thing to different viewers, because the designer has chosen and inserted a specific object into the model. Each viewer would be able to look up the object definition and, for example, know which wall type was used.

Many parts of the building are not shown on the drawings in either the new or traditional design process. Specifications represent many "hidden" parts of the building, while other building parts, such as wiring, are shown schematically. Actual wiring location is typically decided by the electrician actually doing the task.

Successful use of new object-oriented design technologies will depend on several factors:

- How does the tool facilitate architectural layout?
- Can the designer select from a complete palette or library of 3-D objects needed to represent walls, doors, windows, building systems, etc.?
- Can the designer add unique 3-D objects to the library when needed?
- How easy is it for users to view the design representation and understand both design intent and the chosen building products and systems? This information may not be displayed as traditional drawings or specifications, but may instead be represented in a hierarchical list.
- Is the designer able to generate a complete set of construction documents?
- Are the construction documents understandable by the owner, construction manager, and contractors?

Current Trends

USACERL is in the process of incorporating lessons learned and functional capabilities developed during the testbed project into the Modular Design System (MDS) (USACE, January 1997). Future versions of MDS will enable designers not only to design collaboratively, but also to identify and resolve conflicts from different physical locations.

USACERL researchers also are actively involved in the development of Industry Foundation Classes (IFC) as part of the International Alliance for Interoperability (IAI). Our experience in developing a shared facility model for the testbed helps us collaborate with others in this international effort to develop a shared library of object foundations classes for A/E/C software. Software that is IFC compliant will be able to import and export design files that other IFC-compliant software generate. For example, an architect can layout a building, then share the files with the structural, electrical, and mechanical engineers who design the appropriate building systems. A cost estimator with IFC-compliant software would be able to generate a cost estimate using the same design files, without recreating information. Future versions of MDS will also be IFC compliant, which will allow us to gain access to other IFC compliant A/E/C software tools (http://www.interoperability.com).

Product manufacturers have begun to provide tools that enable designers to insert brand name 2-D and 3-D objects such as toilets and windows into design files. In the near future, manufacturer-supplied objects will be available to

designers via CD-ROM or the Internet. Designers would be able to select "generic" building product objects for early design, and possibly replace them later with specific objects during final design, or once the contractor has selected a particular product from a manufacturer. If these 3-D facility models are structured properly, accurate as-built information may be collected and associated with the proper objects. Then accurate as-built information would be available for facility managers, operations personnel, owners, and others throughout the life of the facility.

A/E/C software vendors are actively improving the capabilities of their commercial design tools. Many companies are participating in IAI and are incorporating object-oriented technologies into their software packages. Companies are working on development of web servers for CADD drawings, object models, and libraries of design objects. Private A/E firms and construction companies are collaborating together on projects and using the Internet and world wide web to share and distribute information. The Global Construction Network is a good example of partnering between private companies using the Internet (see http://www.gcn.net). Document management software is improving enough to allow companies to securely manage file access and sharing for large design and construction projects. Work flow management software helps companies route documents through their approval process electronically. "Data warehousing" is developing to the extent that organizations can securely store and manage large archives of electronic documents. Together, these capabilities will enable the A/E/C industry to collaboratively create 3-D models of facility designs, build the facilities, collect accurate as-built data, and share the information throughout the facility's life cycle.

Future Research

The following topics were found to require additional research:

Representation: Research is needed to determine the best ways to represent design intent, and building products and systems which 3-D facility models comprise.

Construction Document Generation: Construction document generation from 3-D models will require a significant research effort. An opportunity exists to greatly reduce the time required to generate construction documents and improve their accuracy and legibility.

Conflict: The testbed project verified that conflict identification, negotiation, and resolution can be accomplished during collaborative design with a shared facility model in a tightly coupled environment. Future work should include an in-depth examination of how conflicts can be resolved among agents and users. Conflict identification and resolution is not yet a capability available in commercial A/E/C software, and many research issues remain.

Loosely Coupled Collaboration: Not shown in this demonstration is how agents and systems that are loosely coupled to each other can interact. The Agent Collaboration Language (ACL) project managed by USACERL involving Stanford University, CMU, MIT, and UIUC explored how to design a building on the information super-highway. Project participants are dispersed throughout the United States and use a wide variety of representations.

Object Server: The shared library representation used in the test bed demonstration proved to be inefficient, in that libraries of frames mimicking this representation had to be created for each software environment. This practice was prone to inconsistencies. Future research will test the feasibility of an "object server." The object server will be responsible for providing frame descriptions of unknown objects that a participant receives via VWS, thereby extending the capabilities of a user's workspace. Quite possibly these representation schemes will become standard within a discipline and/or domain, and an object-server method of sharing representations will effectively facilitate the sharing of objects. Research on how to manage shared-object repositories and model servers to make them available to distributed design teams over the Internet has begun, but more research is needed to assure commercial viability for large scale projects.

Assemblies: It is often desirable to copy portions of an existing design into new work to reduce duplication of effort. Future research will investigate how to facilitate the storing and sharing of groups of objects or "assemblies."

Conclusion

A fully implemented collaborative environment will significantly improve the quality of decision making, contract documentation and related design processes. Through agent-assisted collaboration, the extended design group (including O&M and other installation personnel) works as a coordinated team. Software agents will assist designers in making optimal decisions through improved information dissemination and conflict management. Designers will have the

capability to effectively consider a wider variety of design solutions and evaluate additional alternatives to improve the quality, health and comfort, energy efficiency, and life-cycle cost effectiveness of the facility. Making these types of analyses easy to perform will provide facilities that perform better functionally and at reduced operational expense.

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Acronyms

ACE	Agent Collaboration Environment
ACL	Agent Collaboration Language
A/E/C	Architectural/Engineering/Construction
AEPIC	Architectural/Engineering Performance Information Center
API	Application Programming Interface
BCO	biddability, constructibility, and operability
BLAST	building load and system thermodynamics
CAD	computer-aided drafting
CADD	computer-aided drafting and design
CAFMS	computer-aided facility management system
CE	collaborative engineering
CERF	Civil Engineering Research Foundation
CODBPAT	cost of doing business process action team
COTS	commercial off-the-shelf
CPACE	current persistent ACE
CPM	critical path method
CRaDA	Cooperative Research and Development Agreement
DDE	dynamic data exchange
DOD	Department of Defense
EMS	Engineering Management Systems
ER	Engineering Regulations
ETL	engineering technical letters
FY	fiscal year

HQUSACE	Headquarters, U.S. Army Corps of Engineers
IAI	International Alliance for Interoperability
IFC	industry foundation classes
KIF	knowledge interchange format
KQML	knowledge query and manipulate language
MACOM	Major Army Command
MAP	master action plan
MCA	Military Construction, Army
MCACES	MCA cost estimate system
MDS	Modular Design System
MILCON	military construction
O&M	operations and maintenance
OML	object modeling language
O-O	object-oriented
PE	project engineering
R&D	research and development
RMS	Resident Management System
TQM	Total Quality Management
USACE	U.S. Army Corps of Engineers
USACERL	U.S. Army Construction Engineering Research Laboratories
VWL	Virtual Workplace Language
VWS	Virtual Workplace System
WES	Waterways Experiment Station

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